VOL. 255 NOVEMBER 1957 No. 9

American Journal of Science

Established in 1818 by Benjamin Silliman

EDITORS
JOHN RODGERS—JOSEPH T. GREGORY

ASSOCIATE EDITORS

REGINALD A. DALY, CAMBRIDGE, MASS.
A. F. BUDDINGTON, PRINCETON, N. J.
CARL O. DUNBAR
MATT WALTON
HENRY MARGENAU
RICHARD F. FLINT
HORACE WINCHELL
HAROLD G. CASSIDY
EDWARD S. DEEVEY, JR.
G. EVELYN HUTCHINSON
NEW HAVEN, CONN.
LEASON H. ADAMS
WILMOT H. BRADLEY
WASHINGTON, D. C.
GEORGE GAYLORD SIMPSON, NEW YORK, N. Y.
HOWEL WILLIAMS, BERKELEY, CALIF.
C. R. LONGWELL, PALO ALTO, CALIF.
ADOLPH KNOPF, STANFORD, CALIF.
FREDERICK J. ALCOCK, OTTAWA, CANADA
CECIL E. TILLEY, CAMBRIDGE, ENGLAND

STERLING TOWER
YALE UNIVERSITY
NEW HAVEN, CONNECTICUT

Published 10 times a year. Ten dollars a year. One dollar twenty-five cents a copy.
Foreign, ten dollars sixty cents Canada, ten dollars thirty-five cents.

AMERICAN JOURNAL OF SCIENCE

Established in 1818 by Benjamin Silliman

THE FIRST SCIENTIFIC JOURNAL IN THE UNITED STATES

DEVOTED TO THE GEOLOGICAL SCIENCES AND TO RELATED FIELDS

Editors: JOHN RODGERS—JOSEPH T. GREGORY

Managing Editor: BETH A. BROMBERT

Entered as second-class matter at the Post Office at New Haven, Conn., under the Act of March 3, 1879. Published monthly, except July and September, at Sterling Tower, Yale University, New Haven, Conn.

Subscription rate $10 per year ($1.25 a number). Student rate $5 per year (application blanks available on request). Postage prepaid to the United States; 35 cents per year to Canada; 60 cents per year elsewhere.

The JOURNAL completed its *first* series of 50 volumes in 1845, its *second* series of 50 volumes in 1870, its *third* series of 50 volumes in 1895, its *fourth* series of 50 volumes in 1920, its *fifth* series of 36 volumes in 1938. Since 1938 the numbering by series has been discontinued, and volumes are annual and bear the whole numbers as of 1818, that for 1939 being volume 237.

Back numbers and volumes, also cumulative indices of all series, may with few exceptions be obtained from the office of the AMERICAN JOURNAL OF SCIENCE, Sterling Tower, New Haven, Conn. Positive microfilm copies of each complete volume may be purchased by subscribers to the paper edition from *University Microfilms*, 313 N. First St., Ann Arbor, Michigan. Regular subscribers may purchase each past year in microcard form, from *The Microcard Foundation*, Wesleyan University, Middletown, Connecticut.

INSTRUCTIONS TO CONTRIBUTORS

Manuscripts of articles submitted should follow the recommendations in the pamphlet "Suggestions to Authors" (Lane, 1935) and should be preceded by brief abstracts. They should be checked with special care before being submitted, to avoid changes in proof other than printer's errors.

References to literature should be listed alphabetically by authors at the end of the article; all references should be complete. For articles in journals or other serial publications, the reference should give in order: Author's name, year of publication, full title: name of periodical or series, volume number, inclusive pages. For books or other unnumbered publications, it should give: Author's name, year of publication, full title: place of publication, publisher. This form follows the recommendations in the pamphlet "Abbreviations used in publications of the U. S. Geological Survey", which is also the standard used for abbreviating names of periodicals, etc. Citations within an article should be to author and year, with specific pages wherever appropriate.

Plates (photographs), *figures* (line drawings), and *footnotes* should each be numbered consecutively through each article, using arabic numerals. If two photographs form one plate, they are figures 1 and 2 of that plate.

Illustrations should be neat and legible and should include explanations of symbols used. Copy that cannot be reproduced cannot be accepted. Plates and figures should be capable of reduction to not more than 4 by 7 inches, all lettering being at least 1/16th inch high after reduction. When necessary, one large map or table can be accepted, if it will not exceed 7 inches in width after reduction. Line drawings should be in black India ink on white drawing board, tracing cloth, or coordinate paper printed in blue. Photographs should be positive glossy prints. Photostatic and typewritten material cannot be accepted as copy for illustrations.

Reprints. Thirty separate copies of each article will be furnished to the author free of cost and without previous notice from him; these will be without a cover. Additional copies will be furnished at cost, which will of course be greater if the article is accompanied by plates involving unusual expense. Copies will be furnished with a printed cover giving the title, author, volume, page, and year, when specially ordered.

REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 40c.)

[American Journal of Science, Vol. 255, November 1957, P. 607-618]

American Journal of Science

NOVEMBER 1957

POSSIBLE PERMIAN CLIMATIC ZONATION AND ITS IMPLICATIONS

FRANCIS G. STEHLI*

ABSTRACT. Zoogeographic patterns shown by some groups of Permian brachiopods and fusulinids indicate a northern range limit lying between 50° and 60° N lat. Analogy to Recent and Cretaceous zoogeography suggests that this boundary indicates the position of the boundary between temperate and subtropical water conditions. If this is true, post-glacial Permian climate was considerably milder than that of the present. Parallelism of what is believed to be a temperature-controlled Permian faunal discontinuity with the present equator suggests that northern hemisphere continental relationships during the Permian were essentially those of today. Shift of the mantle with apparent displacement of the poles since the Permian is also denied by the data if the interpretation presented is correct.

INTRODUCTION

The climate of the Permian period has long aroused interest and speculation not only for itself but for its bearing on continental relationships. Attention has focused primarily on the climatic conditions responsible for "Permo-Carboniferous" glaciation in the southern hemisphere. The causes of glaciation are imperfectly understood, however, and the climatic implications of an ancient glacial interval cannot yet be adequately interpreted. Of more general interest, and more readily subject to interpretation, is the post-glacial Permian climate for it appears to initiate an aglacial episode which persisted until the Pleistocene. The climate of this interval probably approximates the normal climate of the earth. Although the oxygen isotope paleotemperature method of climatic study used by Lowenstam and Epstein (1954) would be ideal for a study of Permian climate, no material in a usable state of preservation has yet been found. It is thus necessary to turn to some other means of evaluating Permian climate. Of those available, zoogeographic study appears most promising.

In this study an attempt has been made, using the geographic ranges of some groups of Permian marine invertebrates, to obtain evidence of the nature of Permian climate. Plots of the world distribution of these groups reveal a striking pattern which seems to indicate the existence of climatic zonation. There are a great number of variables and imponderables which hamper precise evaluation of even the best zoogeographic data; nevertheless useful general results may be obtained and seem worthy of consideration in relation to the problems of past climate despite their qualitative nature.

PROCEDURE

Only relatively well-known invertebrate groups were considered, in the hope that the uncertainties introduced by systematics could thus be reduced to a minimum. The writer has selected certain brachiopod groups with which he

* Pan American Petroleum Corporation, Research Center, Tulsa, Oklahoma.

is familiar and has selected fusulinids because they seem to be the most extensively studied group of Permian invertebrates. Within these two groups a search was made for taxa which showed restricted distribution patterns. Initial distribution data were drawn from Branson (1948) who gives locality information for Permian invertebrate species described up to 1941 and for those described in accessible literature up to June, 1946. Supplementary information on more recently described forms was obtained from the Zoological Record and references listed there. The data are reasonably complete to 1952. A recent monograph on Greenland Permian Brachiopods by Dunbar (1956) was also employed to improve the sparse high latitude coverage.

The subjectivity apparent in species assignments made it evident early in the study that only genera or larger taxa could be employed. Distributional plots on world maps were made for a number of familiar forms. These plots showed that only two clearcut distribution patterns were present. One was a random or world-wide pattern; the other was restricted to a world-encircling belt limited to middle and low latitudes. Plots were then made for a large number of additional forms in an effort to determine whether the range limitations were random or coincided at some important zoogeographic break. The range limitations proved to be similar in each case insofar as the sampling, discovery and extent of study permitted comparison.

There is ample evidence that, within limits, climate is in constant fluctuation. Zoogeographic data to be used in consideration of climate should therefore relate to the shortest possible interval of geologic time. Unfortunately changing opinion on world-wide intra-Permian correlation and the paucity of data for short time intervals have forced the use of the entire Permian period. Further temporal refinement would be possible in many areas, but could not be carried with confidence throughout the world. Therefore, the distribution patterns must be regarded as maximum rather than minimum or average ranges during the Permian; they are clearly composite in nature, and are highly generalized.

For the purposes of this study the base of the Permian was considered to be at the base of the Sakmarian and equivalent strata. Many localities in the southern hemisphere and in the USSR have been ambiguously designated "Permo-Carboniferous". Those which seem to me clearly Pennsylvanian have been omitted from the plots. In no case, however, would inclusion of these data alter the observed distributions significantly.

Localities were plotted from original references wherever latitude and longitude were listed or maps were present. Others were located in an atlas and plotted. This latter procedure may have introduced errors in location of some points, but it is believed that errors of this kind were minor.

Data.—Figure 1 is a plot on a world map of the distribution of the better known outcroppings of fossiliferous Permian marine rocks. It is introduced to serve as an indication of the sampling restrictions imposed by the available data. It will be noted that data are inadequate in the southern hemisphere which is little studied, consists largely of water, and contains no known marine Permian outcrops at latitudes higher than about 45°S.

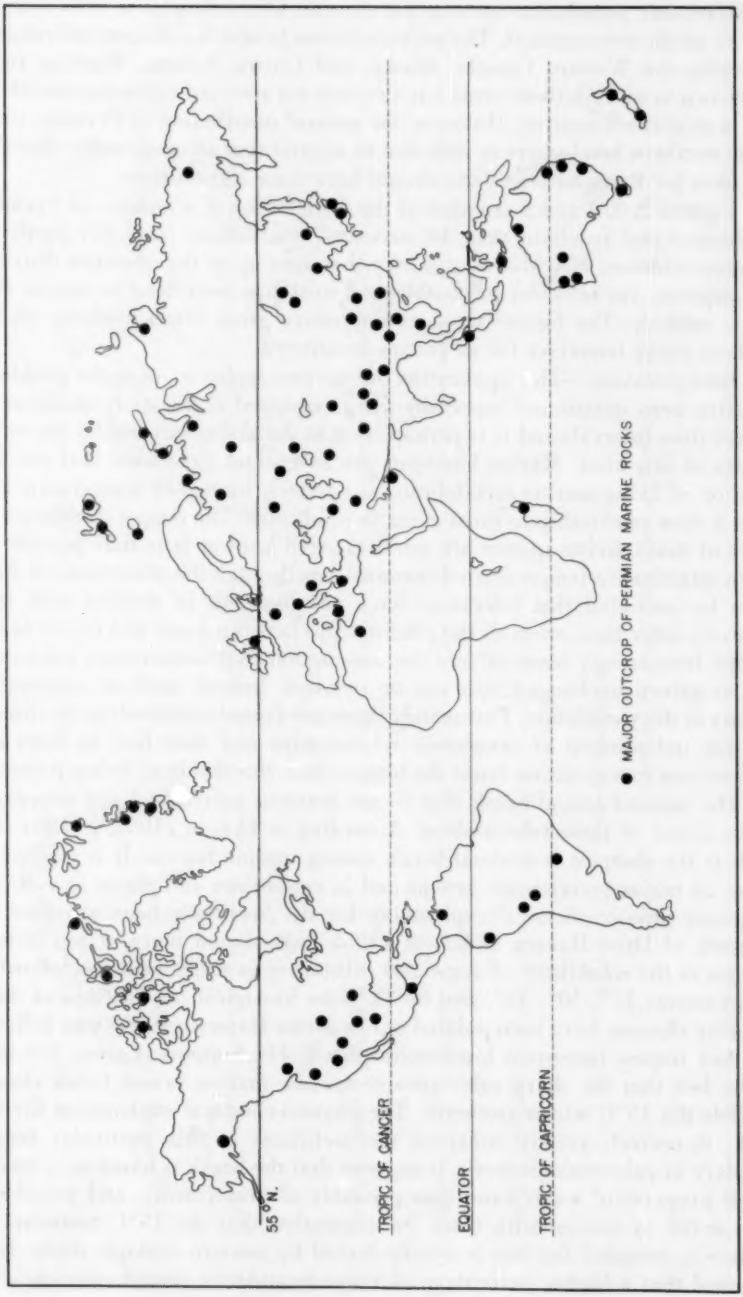

Fig. 1. Control map indicating major areas with outcropping marine Permian rocks.

In the northern hemisphere data seem adequate. Investigations have been extensive near population centers, but considerable information also is available on arctic outcroppings. The principal areas in which sufficient information is lacking are Western Canada, Alaska, and Central Siberia. Permian rocks are known to exist in these areas but have not yet received extensive consideration in available literature. However, the general distribution of Permian rocks in the northern hemisphere is sufficient to suggest that zoogeographic-distribution plots for Permian organisms should have some significance.

Figures 2, 3, 4 and 5 are plots of the distribution of a number of Permian brachiopod and fusulinid taxa. Of necessity, distribution plots rely partly on negative evidence. New discoveries may therefore upset the observed distribution patterns, but sufficient paleontological work has been done to suggest that this is unlikely. The figures show an impressive gross correspondence on the northern range boundary for all groups considered.

Interpretation.—The application of zoogeography to climatic problems has often been questioned, especially when employed in the study of the more ancient time intervals and it is perhaps best at the outset to consider the value of data of this kind. Marine biologists are in general agreement that the distribution of living marine invertebrates is narrowly limited by temperature and bears a close relatonship to gross climatic conditions. The temperature requirements of many living species are relatively well known. It is thus possible to obtain quantitative temperature determinations through the time range of these forms by assuming that tolerances have not changed. In dealing with progressively older time intervals the relationships between fossil and recent forms become increasingly tenuous, and the assumption that temperature tolerances have remained unchanged may not be justified. Indeed, such an assumption appears to deny evolution. Fortunately there are faunal relationships to climate that are independent of taxonomic relationships and thus free us from dependence on extrapolation from the temperature thresholds of living forms.

The marked faunal break that occurs between subtropical and temperate faunas is one of these relationships. According to Ekman (1953, p. 186) this break is the sharpest latitudinal break among marine faunas. It is evident in almost all major invertebrate groups and in vertebrates and plants as well. An intriguing physico-chemical explanation for the break has been provided by the work of Drost-Hansen and Neill (1955) who found more or less abrupt changes in the solubilities of some 200 substances in water near the following temperatures: 15°, 30°, 45°, and 60°C. Some biological implications of these solubility changes have been pointed out by Drost-Hansen (1956) who believes that they impose important biochemical thresholds. Support is given this idea by the fact that the sharp subtropical-temperate marine faunal break closely parallels the 15°C winter isotherm. The physico-chemical explanation for the break, if correct, greatly enhances the usefulness of this particular faunal boundary in paleoecologic work. It suggests that the break is based on a fundamental property of water (and thus probably of protoplasm), and would not be expected to change with time. No suggestion that the 15°C boundary is absolute is intended for this is clearly denied by modern ecologic study. It is suggested that a higher percentage of range boundaries should coincide with

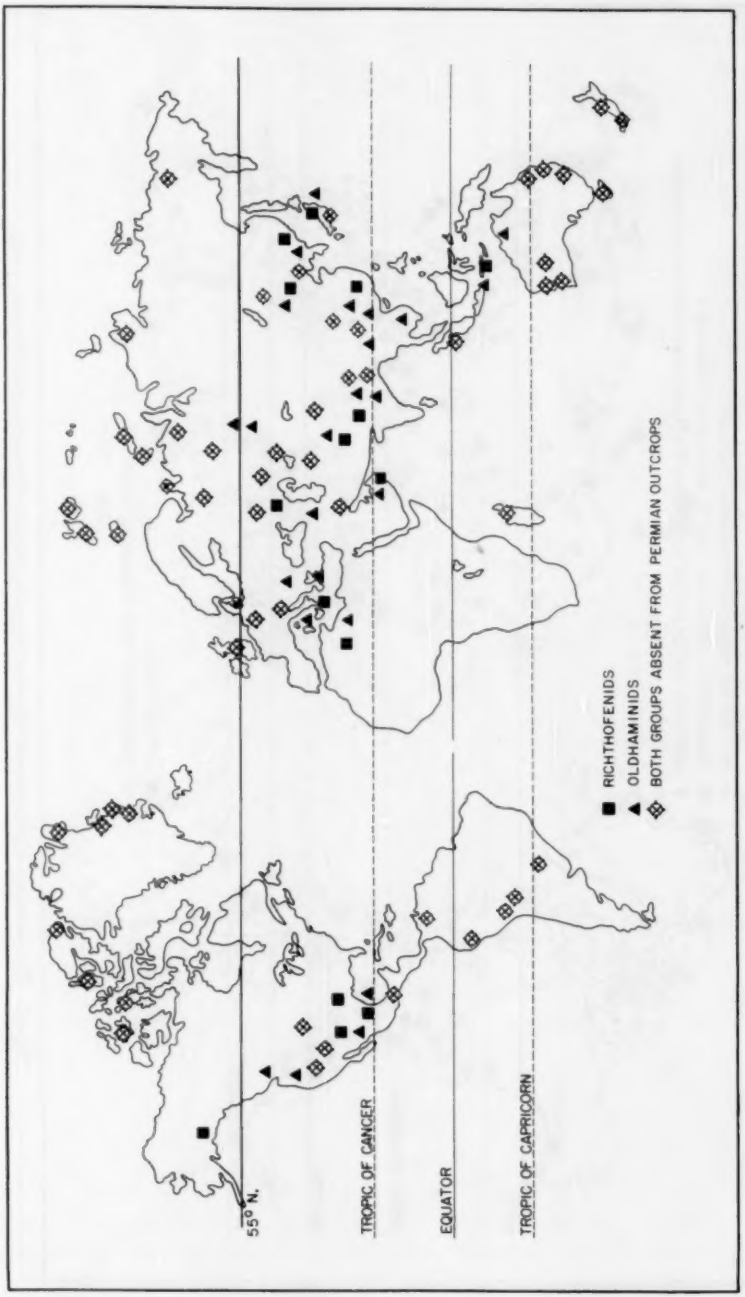

Fig. 2. Plot showing distribution of Richthofenid and Oldhaminid brachiopods in Permian rocks.

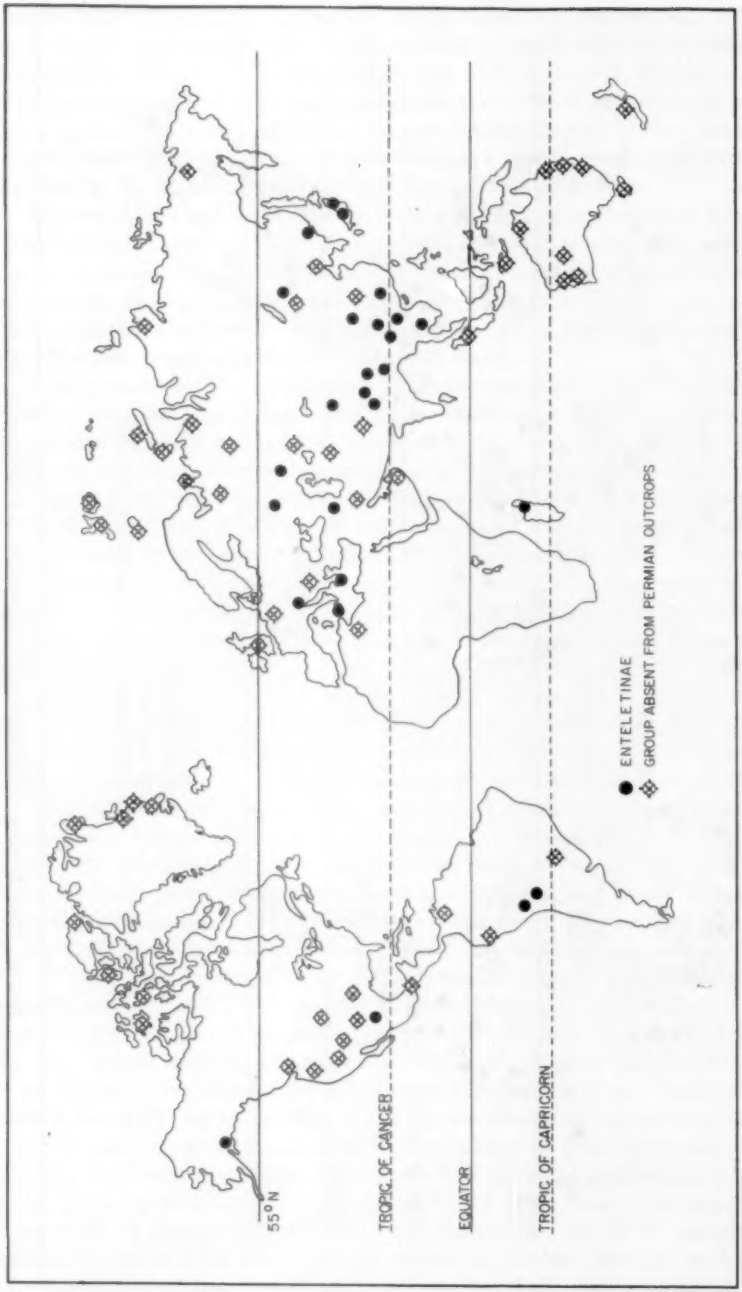

Fig. 3. Plot showing distribution of the brachiopod subfamily Enteletinae in Permian rocks.

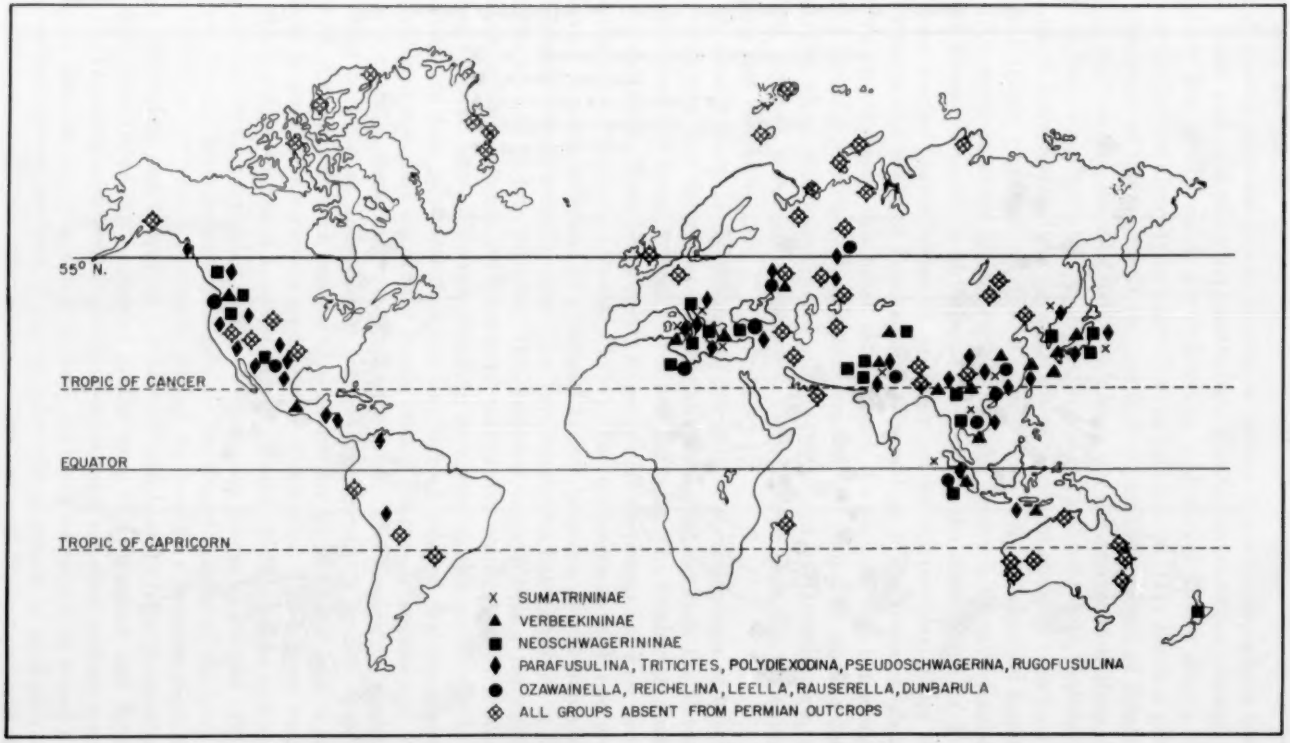

Fig. 4. Plot showing distribution of various fusulinid groups in Permian rocks.

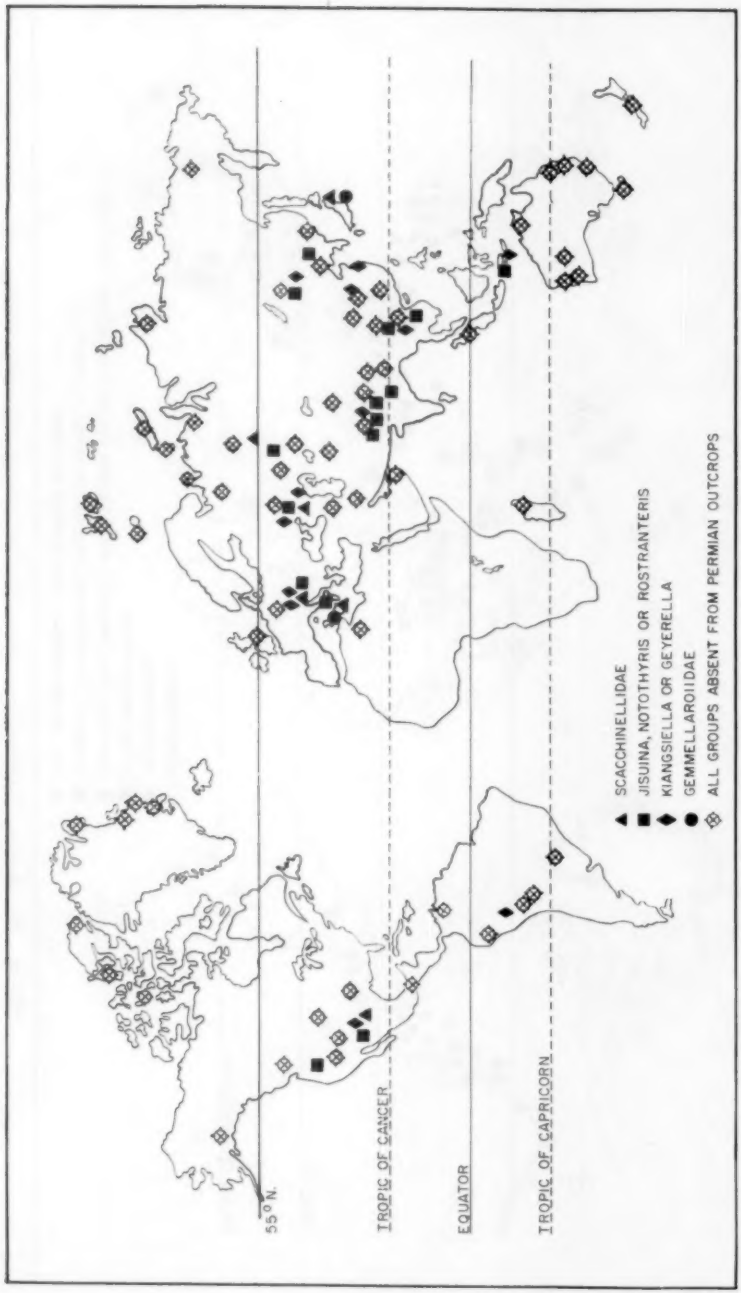

Fig. 5. Plot showing distribution of various brachiopod groups in Permian rocks.

the 15° isotherm than with neighboring isotherms and that this should always have been the case.

A second relationship can be seen in groups of marine organisms having both warm and cold water representatives. Marine invertebrates (except in a relatively few groups which are endemic to cold water) almost always show greater taxonomic diversity in warm than in cold waters. This does not permit the placement of sharp boundaries, but it does provide a means of determining, in any traverse, the direction which leads toward warmer conditions. Employing these zoogeographic principles, and given sufficient data, it should be possible to learn much about the generalities of ancient climates even for time intervals within which we are forced to deal exclusively with extinct forms.

The northern range boundary shown in the figures is the only consistent faunal break observed in the course of plotting the distribution of many Permian marine invertebrates. It probably marks the position of the most persistent faunal break of Permian time. By analogy to the impirical data of modern zoogeography this break should mark the position of a temperature-related boundary between Permian subtropical and temperate marine conditions. The physico-chemical considerations introduced by Drost-Hansen, suggesting a sharp temperature-dependent faunal break near the same point, support this conclusion.

A consideration of the taxonomic diversity of several groups of brachiopods indicates that there was a temperature gradient between the Permian deposits presently found at high and at low latitudes. The Productacea which are represented in West Texas by 20-30 genera are represented in East Central Greenland by 10 genera (Dunbar, 1956). The Orthotetacea with one genus restricted to high latitudes, 11 restricted to low latitudes, and 4 common to both areas presents a similar case. The Terebratuloidea have 2 genera in high latitudes and 13 in low latitudes. This evidence suggests that a temperature gradient existed between cold northern waters and warm equatorial waters during Permian time. Although sampling in regard to this parameter is not adequate, the data, wherever they can be obtained, suggest that the temperature gradient was from the present Arctic toward the present equator.

To evaluate better the zoogeographic study of climates, it would be desirable to have an independent method against which results could be checked. Although no such method is available for the Permian, such a comparison is possible for certain parts of the Cretaceous. The oxygen isotope paleotemperature studies of Lowenstam and Epstein (1954) can be compared with the earlier zoogeographic studies of Cretaceous faunas by Dacqué (1915). Dacqué, basing his conclusions largely on the zoogeography of the long extinct (60-70 x 10^6 years) Rudistids, placed the boundary between the Cretaceous subtropical and temperate (or tethyan and boreal) belts in essentially the same position as that suggested by the work of Lowenstam and Epstein (1954). The agreement between zoogeographic and paleotemperature studies indicates that the zoogeographic method, critically employed, is sound even when extinct groups are used. Zoogeography may therefore be profitably employed in a study of time intervals beyond the range of the isotope method.

Evidence exists to show that the subtropical-temperate temperature boundary for both the Cretaceous and the present occurred near the 15°C isotherm and coincides with the sharpest observable faunal break. During the post-Aptian Cretaceous this boundary, although fluctuating somewhat, appears to have maintained a position in Europe near 55°-60°N (Lowenstam and Epstein, 1954, fig. 11; Dacqué, 1915). It is interesting to note, therefore, that the sharp fanual break of the post-glacial Permian falls at approximately the same latitude as that of the Cretaceous as this strengthens the possibility that the faunal break is due to temperature control. The deviation of the same faunal break today from this position is probably due to our present glacial climate.

The present 15°C winter isotherm varies in position through more than 15° of latitude under the influence of warm and cold currents (Sverdrup, Johnson and Fleming, 1946, Chart II). It may be expected that a similar situation existed during the Permian. To this inherent variability must be added deviations resulting from the vagaries of preservation and discovery. Clearly no definitive latitudinal boundary is to be expected on the distribution plots.

In considering the distribution plots there appeared to be some possibility that the patterns observed might be due to chance. In order to set some confidence limits, a statistical evaluation was attempted. It was assumed that the distribution of the animals concerned was homogeneous over the entire earth. It was further assumed that the probability of finding a given animal at any sampling station was represented by the number of occurrences over the total number of sampling stations between the equator and 65° N. The boundary at 65° N was arbitrarily selected because it separated the area of occurrence from the area of complete non-occurrence. With these assumptions an evaluation was made of the probability of sampling the 16 localities north of 65° without encountering a single occurrence. Such a calculation was performed for each of the entities used as a plotting unit in figures 2-5. Consideration of the results (see table 1) indicates that it is unlikely that any of the patterns is

TABLE 1

Figure 2—Richthofenids	—Distribution would occur by chance						6 in	1,000 times
2—Oldhaminids	—	"	"	"	"	"	1 in	10,000 "
3—Enteletinae	—	"	"	"	"	"	7 in	10,000,000 "
4—Sumatrininae	—	"	"	"	"	"	122 in	1,000 "
4—Verbeekininae	—	"	"	"	"	"	19 in	1,000 "
4—Neoschwagerininae	—	"	"	"	"	"	11 in	1,000 "
4—Parafusulina, etc.	—	"	"	"	"	"	9 in	100,000 "
4—Ozawainella, etc.	—	"	"	"	"	"	74 in	1,000 "
5—Scacchinellidae	—	"	"	"	"	"	174 in	1,000 "
5—Jisuina, etc.	—	"	"	"	"	"	12 in	1,000 "
5—Kiangsiella, etc.	—	"	"	"	"	"	48 in	1,000 "
5—Gemmellaroiidae	—	"	"	"	"	"	157 in	1,000 "

Explanation: Probability that the observed distribution would occur by chance under the assumptions noted for each taxonomic group.

due to chance. One must assume therefore that some environmental condition limited the distribution of the animals whose ranges are plotted. This environmental condition is here considered to have been temperature.

Climate and Continental Relationships.—Climatic information about ancient time intervals has considerable intrinsic interest in relation to paleobio-

logical and geochemical problems but can also be brought to bear on certain geophysical problems. Variations in the average temperatures of the earth's surface are primarily related to the capture of radient energy and the effectiveness of capture varies with latitude. Isotherms therefore must be grossly parallel to the earth's equator. If the relationship between ancient isotherms and the present equator of the earth can be established, a means is at hand for evaluation of the hypothesis of continental drift, at least insofar as major change in the latitudinal positions of the land masses is concerned. This is true irrespective of whether drifting takes the form of a relative motion between continents or a general slipping of the mantle or crust about the core. Zoogeographic data can also be used in an evaluation of data on remanent magnetism in ancient rocks as long as it is assumed that the magnetic and rotational poles of the earth were closely associated.

The suggestion has been made above, on the basis of several concurrent lines of evidence, that the northern range boundary shown for several groups of Permian marine invertebrates in figures 2-5 is the result of a temperature barrier. It is considered most probable that this barrier is between the subtropical and temperate marine temperature zones of Permian time and is roughly coincident with the 15°C winter isotherm of the Permian. Even if the latter interpretation should be incorrect, a strong probability exists that the break is caused by temperature, as scattered evidence shows that it runs roughly normal to the temperature gradient of Permian time.

If the interpretation that the faunal discontinuity is the result of temperature is correct, the position of the break may be equated with the position of a Permian isotherm whether it be the 15°C isotherm or some other, and must therefore approximately parallel the Permian equator. Examination of figures 2-5 shows that this boundary is parallel to the present equator as well. This being so, it follows if the argument is accepted, that the positions of the earth's poles cannot have shifted with respect to northern hemisphere land masses since Permian time. The inference from these data that the poles occupied approximately their present positions in the Permian is in complete disagreement with the interpretation of remanent magnetism data by Runcorn (1956) who suggests that the Permian north pole was in a position within what is here believed to have been the tropical and subtropical temperature belt of Permian time.

CONCLUSIONS

A sharp boundary to the apparent ranges of a number of Permian marine invertebrates occurs between 50° and 60° N wherever data permit its location. The boundary is believed to be temperature controlled and probably to represent the position of the interface between the Permian subtropical and temperate marine temperature belts. The faunal boundary parallels the earth's present equator and, if truly caused by temperature, precludes the possibility of changes in the position of the poles with respect to the major land masses of the northern hemisphere. Also precluded is the possibility that the crust or mantle has shifted its position relative to the core. The data are not in accord with data derived from remanent magnetism of rocks.

References

Branson, C. C., 1948, Bibliographic index of Permian invertebrates: Geol. Soc. Amer., Mem. 26, p. 1-1049.

Dacqué, E., 1915, Grundlagen und methoden der paleogeographie: Jena, Gustav Fisher, p. 1-499.

Drost-Hansen, W., 1956, Temperature anomalies and biological temperature optima in the process of evolution: Die Naturwissenschaften, v. 43, no. 22, p. 512-513.

Drost-Hansen, W. and Neill, H. W., 1955, Temperature anomalies in the properties of liquid water: Phys. Rev., v. 100, p. 1800.

Dunbar, C. O., 1956, Permian Brachiopod Faunas of Central East Greenland: Medd. om Grønland, Band 110, nr. 3, p. 1-172.

Ekman, S., 1953, Zoogeography of the sea: London, Sedgwick and Jackson, Ltd., p. 1-417.

Lowenstam, H. and Epstein, S., 1954, Paleotemperatures of the Post-Aptian Cretaceous as determined by the oxygen isotope method: Jour. Geol., v. 62, no. 3, p. 207-248.

Runcorn, S. K., 1956, Paleomagnetic survey in Arizona and Utah, preliminary results: Geol. Soc. Amer. Bull., v. 67, p. 301-316.

Sverdrup, H. V., Johnson, M. W. and Fleming, R. H., 1946, The oceans, their physics, chemistry and general biology: New York, Prentice-Hall, Inc.

Zoological Record, 1946-1954, published by the Zoological Soc. of London, v. 83-91.

[American Journal of Science, Vol. 255, November 1957, P. 619-627]

TEMPERATURE ESTIMATION OF PYROCLASTIC DEPOSITS BY NATURAL REMANENT MAGNETISM

SHIGEO ARAMAKI and SYUN-ITI AKIMOTO

ABSTRACT. The formation temperature of pyroclastic deposits can be estimated by measuring the orientation of natural remanent magnetism of the fragments contained in the deposits. If the N. R. M. has a uniform orientation in all the fragments, the formation temperature was higher than the Curie point of the constituent ferromagnetic mineral, provided that the N. R. M. originated from the stable thermo-remanent magnetism. If the fragments show a random orientation of N. R. M., the formation temperature was lower than the Curie point. Examples of the random and uniform orientation from several pyroclastic deposits are reported. By this means, nuée ardente deposits can be distinguished from mud flow deposits.

INTRODUCTION

Many types of clastic deposits are known to have been produced by volcanic activity, for example, tuff, tuff-breccia, pumice and scoria fall deposits, agglomerate, agglutinate (according to the classification of Wentworth and Williams, 1932), pyroclastic flow (or nuée ardente in the broad sense of the term) deposits, and—if we include agencies other than volcanic eruption —many kinds of mud flow deposits. These pyroclastic deposits vary greatly in character, and their modes of emplacement are in some cases difficult to conjecture.

One problem is the estimation of the temperature of their formation. Mud flow deposits and some tuff, tuff-breccia, pumice and scoria fall deposits are formed at atmospheric temperatures, while agglomerate, agglutinate, pyroclastic flow deposits, and some tuff, tuff-breccia, pumice and scoria fall deposits are known to be deposited at the temperatures very close to that of magma. When no record of direct observation of the deposition is available, geologists usually distinguish these high temperature pyroclastic deposits from the low temperature ones by the nature of the component blocks or the presence of burnt wood fragments. These criteria are sometimes not conclusive, however. The new method here proposed, the measurement of the orientation of natural remanent magnetism, affords probably the most reliable criterion for the distinction.

If all the fragments composing a deposit maintained a temperature above the Curie point of the constituent ferromagnetic minerals (commonly magnetite and ilmenite) during emplacement and cooled to a temperature below this point only after they came to rest, their thermo-remanent magnetism (T.R.M.)[1], must show a uniform orientation, namely, parallel to the direction of the geomagnetic field of that place at the time of cooling. On the other hand, if the fragments had already cooled below the Curie point before they settled to form the deposit, the natural remanent magnetism (N.R.M.)[2] of the fragments must have random orientations. N.R.M. can be used for geothermometry when it is ascertained that it originated from the stable T.R.M. Nagata (1954) proposed a practical method for testing the stability of N.R.M.

[1] i.e. remanent magnetism caused by cooling, in the geomagnetic field, from a temperature higher than the Curie point.

[2] i.e. residual permanent magnetism possessed by a rock in its natural state.

The present writers measured the N.R.M. of some pyroclastic deposits whose T.R.M. is supposed to be stable and to coincide with N.R.M. It has thus been proved that this method may serve as a geothermometer.

ACKNOWLEDGMENTS

The writers express their sincere thanks to Prof. Hisashi Kuno of the Geological Institute who first suggested estimating the temperature of formation of pyroclastic deposits by measuring their N.R.M. Their thanks are also due to Prof. Takesi Nagata of the Geophysical Institute for his encouragement throughout this study. Mr. Seiya Uyeda of the Earthquake Research Institute kindly helped the writers in measuring the magnetic properties of the samples, and to him they are greatly indebted.

METHODS OF MEASUREMENT

Oriented specimens were taken from blocks and bombs of pyroclastic deposits with the aid of a clinometer. The directions of N.R.M. of these specimens were measured in the laboratory by an astatic magnetometer according to the method described by Nagata (1943, p. 52-60). The results are plotted on the Schmidt equal-area projection net (figs. 1-9). Solid circles represent the directions of the north-seeking poles of the specimens plotted on the lower hemisphere, and crosses those on the upper hemisphere.

All the specimens reported in this paper were collected from fresh andesite and basalt whose component ferromagnetic mineral is exclusively titaniferous magnetite. Therefore, the stability of N.R.M. of these rock specimens may be considered fairly high.

MUD FLOW DEPOSIT OF BANDAI-SAN VOLCANO

A mud flow was caused by the great phreatic explosion of Bandai-san, northeast Japan, which in 1888 destroyed a part of the mountain (Sekiya and Kikuchi, 1890). The shattered material, intermingled with water, dashed toward the north and spread over an area of 70km^2. The explosion was caused simply by pent-up gas pressure, and no juvenile material was issued. The blocks of the mud flow deposit are pyroxene andesite, which formerly constituted the volcano, and therefore must have had their N.R.M. fixed before they were shattered and emplaced by the 1888 explosion. Four oriented specimens were taken from four different blocks in the deposit. Measurement shows a random distribution of the direction of N.R.M. for these specimens (fig. 1). Thus the blocks maintained a temperature below the Curie point of the magnetite in the rock during the emplacement. From the petrographic character of the rock, it is estimated that the Curie point lies between 400°C and 550°C (Akimoto, 1955). It follows then that the temperature of the mud flow must have been lower than this. This conclusion agrees with the observation that the mud flow was emplaced at a low temperature.

MUD FLOW DEPOSIT OF THE CENTRAL CONE OF HAKONE VOLCANO

Another example of random distribution of the direction of N.R.M. is furnished by the mud flow deposit (volcanic conglomerate) of the central cone of Hakone Volcano, central Japan. According to Kuno (1950; 1952, p. 126),

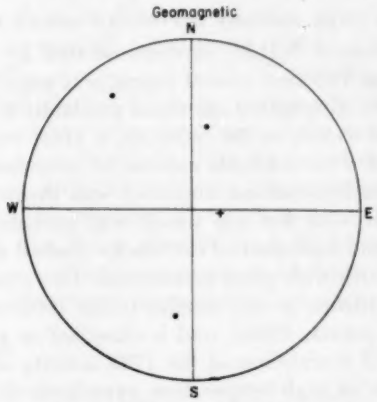

Fig. 1. N.R.M. direction of the mud flow deposit of Bandai-san Volcano. Solid circles are plotted on the upper hemisphere and the cross is on the lower.

this mud flow deposit filled up the gorge of the Hayakawa, which cuts through the caldera wall. The age of the deposit is later Pleistocene. Most of the blocks in the deposit are derived from the central cone lavas (olivine-bearing hypersthene-augite andesite) and the rest from the old and young somma lavas (chiefly pyroxene andesites and dacites). These blocks are more or less rounded by abrasion, and a loose matrix of sand and clay also indicates the low temperature of the deposit. Five oriented specimens from five different blocks exposed at Kawazu-no Taki show a random distribution of the direction of their N.R.M. (fig. 2).

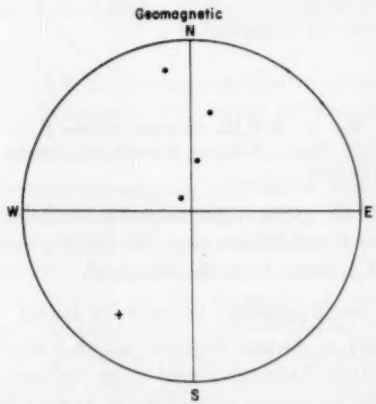

Fig. 2. N.R.M. direction of the mud flow deposit of the central cone of Hakone Volcano. Solid circles are plotted on the upper hemisphere and the cross is on the lower.

KAMBARA NUEE ARDENTE DEPOSIT OF ASAMA VOLCANO

A uniformly oriented N.R.M. is demonstrated by deposits formed by nuées ardentes. Asama Volcano, central Japan, was active for three months in 1783, and the intensity of eruption increased gradually towards the climax on August 5th. About 10 o'clock in the morning, a great explosion took place at the summit crater and a considerable amount of incandescent essential blocks (olivine-bearing augite-hypersthene andesite) was thrown out of the crater. These blocks, together with hot ash which was probably produced by continuous vesiculation and explosion of the blocks, dashed down the slope of the volcano toward the north with great momentum. This pyroclastic flow, named the Kambara Nuée Ardente, is very similar to the 1902 nuées ardentes of Mt. Pelée, Martinique, (Lacroix, 1904), and is classified as a nuée ardente in the strict sense. A detailed description of the 1783 activity of Asama Volcano as well as a classification of high-temperature pyroclastic flows have been given by one of the present writers (Aramaki, 1956, 1957). The direction of N.R.M. of five specimens taken from five different blocks of the Kambara Nuée Ardente is given in figure 3. The concentration of the points in a small area

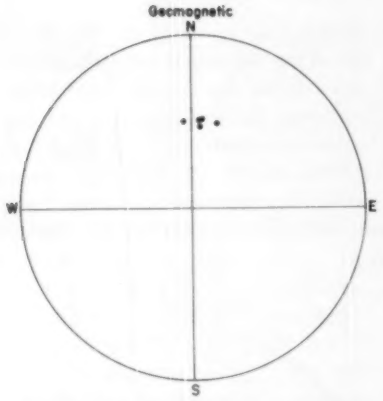

Fig. 3. N.R.M. direction of the Kambara Nuée Ardente deposit of Asama Volcano.

close to the direction of the present geomagnetic field clearly indicates that the temperature of the deposit was higher than the Curie point of magnetite (probably higher than 400°C) at the time of settlement.

AGATSUMA NUEE ARDENTE DEPOSIT OF ASAMA VOLCANO

In the 1783 activity of Asama Volcano, another kind of pyroclastic flow, named the Agatsuma Nuée Ardente, issued from the top crater. It spread over the northern foot of the mountain, probably on August 4th (Aramaki, 1956). This deposit consists of rounded bread-crust bombs and essential ash of the same nature, which is so well indurated as to show rough columnar joints. This pyroclastic flow is a little different in its mode of emplacement and the nature of the composing materials from the Kambara Nuée Ardente and is

classified as a pyroclastic flow of the intermediate type (Aramaki, 1957). Its high temperature at the time of deposition is indicated by the induration of the matrix, carbonization of trees covered by the deposit, formation of a surface oxidation zone, and tree moulds in the deposit. The N.R.M. direction was measured on specimens taken from the bombs at the eastern and the western margin of the deposit (figs. 4 and 5). The concentration of the points is remarkable in both cases, probably reflecting the freshness of the deposit and the ease of sampling at the outcrops. The rock is augite-hypersthene andesite with 62 percent silica. The brown glass in the groundmass carries a considerable amount of opaque particles, supposed to be magnetite dust. The mean value of the specific intensity of magnetization of the specimens (9.1×10^{-3} e.m.u./g) is rather high for the rocks of andesitic composition, perhaps because of the abundance of magnetite dust in the groundmass.

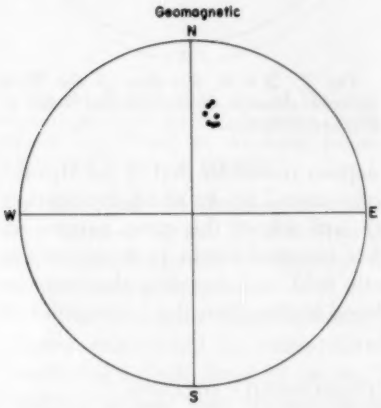

Fig. 4. N.R.M. direction of the Agatsuma Nuée Ardente deposit of Asama Volcano. Samples taken from the eastern margin of the deposit.

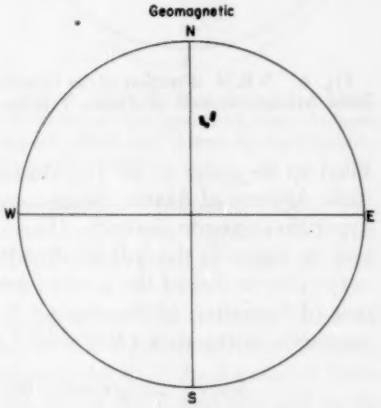

Fig. 5. N.R.M. direction of the Agatsuma Nuée Ardente deposit of Asama Volcano. Samples taken from the western margin of the deposit.

OIWAKE NUEE ARDENTE DEPOSIT OF ASAMA VOLCANO

The Oiwake Nuée Ardente deposit of Asama Volcano also consists of rounded bread-crust bombs and essential ash of augite-hypersthene andesite and covers a wide area (100km^2) on the northern and southern foot of the mountain (Aramaki, 1957). This pre-historic deposit is believed to have been formed by the pyroclastic flow of the intermediate type. It carries many charred logs and shows columnar joints in some places. The uniformity of the N.R.M. direction of four specimens from an outcrop on the southern flank of the volcano (fig. 6) indicates a high temperature for the deposit.

NUEE ARDENTE DEPOSIT OF THE CENTRAL CONE OF HAKONE VOLCANO

Another pyroclastic flow deposit of intermediate type has been found in Hakone Volcano (Kuno, 1950; 1952). The pyroclastic flow issued from one of the central cones of the volcano in later Pleistocene, and its deposit

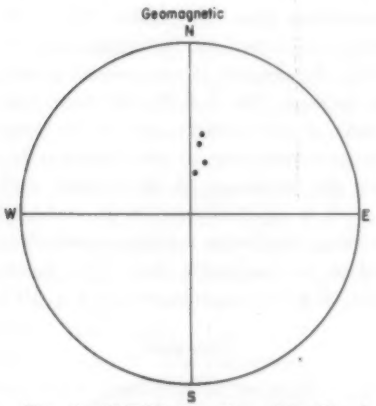

Fig. 6. N.R.M. direction of the Oiwake Nuée Ardente deposit of Asama Volcano.

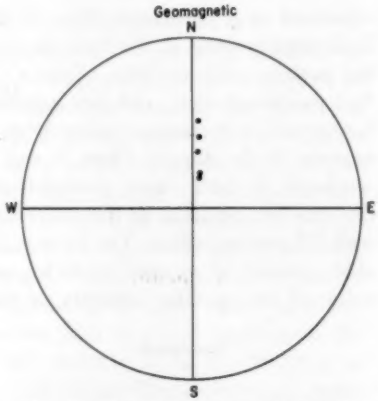

Fig. 7. N.R.M. direction of the Nuée ardente deposit of the central cone of Hakone Volcano.

filled up the gorge of the Hayakawa. The deposit resembles that of the Oiwake Nuée Ardente of Asama, being composed of essential blocks of olivine-bearing hypersthene-augite andesite (Kuno, 1950) and ash of the same nature. As seen in figure 7, the N.R.M. direction of five essential blocks in the deposit is very close to that of the present geomagnetic field, and therefore the temperature of formation of this deposit is considered higher than the Curie point of magnetite in the rock (400°-550°C).

MUD FLOW DEPOSIT OF KO-FUJI (OLD-FUJI) VOLCANO

Along the course of the Ayuzawa River or the upper part of the Sakawa River bordering the north of Hakone Volcano, a thick deposit of mud flow crops out. This mud flow deposit was derived from the material of Ko-Fuji Volcano (later Pleistocene) which underlies the symmetrical cone of the recent Fuji Volcano (Tsuya, 1940; Kuno, 1950). The deposit consists of subangular blocks of olivine-augite basalt up to 2 m across and a large amount of basaltic ash and scoria, which are fairly well indurated. The homogeneous appearance of the matrix, uniformity of composition of the blocks, and presence of irregular-shaped scoriaceous blocks in the deposit seemed to the writers to suggest that it was emplaced in the form of a nuée ardente, in other words, emplaced at a higher temperature than that of an ordinary mud flow. In order to verify this presumption, the N.R.M. measurement was made on the specimens of the blocks in this deposit (fig. 8), which showed, however, a random distribution of the N.R.M. direction. Accordingly, we may conclude that the temperature was lower than the Curie point of the constituent magnetite (probably lower than 500°C).

CONFIRMATION OF THE ERUPTION DATE OF A NUEE ARDENTE BY N.R.M. MEASUREMENT

That the Agatsuma Nuée Ardente was erupted on August 4th, a day before the eruption of the Kambara Nuée Ardente, was inferred indirectly from

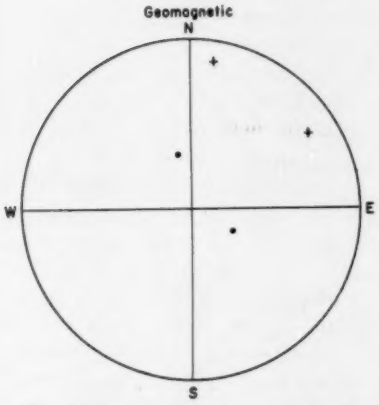

Fig. 8. N.R.M. direction of the mud flow deposit of Ko-Fuji Volcano. Solid circles are plotted on the lower hemisphere and crosses on the upper.

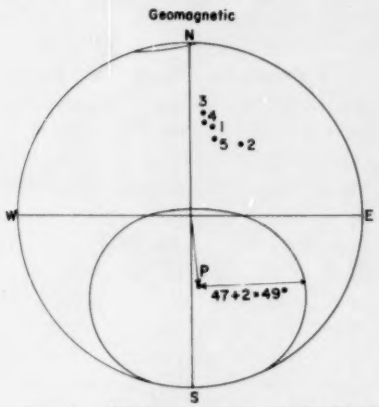

Fig. 9. N.R.M. direction of the block (AS5168) of the Agatsuma Nuée Ardente deposit which was thrown by the Kambara Nuée Ardente.

the study of old documents and field observations (Aramaki, 1956). The measurement of the N.R.M. direction also confirmed this eruption date and eliminated the possibility that this nuée ardente was erupted by older, historic or pre-historic eruption.

The Kambara Nuée Ardente, when it traversed the northern flank of Asama, entrenched the consolidated deposit of the Agatsuma Nuée Ardente, producing a ditch along its course. The shattered blocks of the Agatsuma Nuée Ardente deposit were thrown on both sides of the ditch and are still to be found on its rim (fig. 10). If the bombs of the Agatsuma Nuée Ardente contained in these blocks still maintained a temperature higher than the Curie point of the constituent magnetite when they were thrown on the rim of the ditch, the N.R.M. direction of each bomb must have been oriented parallel to that of the geomagnetic field at the time, regardless of the orientation of the host blocks. The result of the measurement (fig. 9) on five bombs in one of these blocks (AS5168 in fig. 10) shows a concentration of the points in the

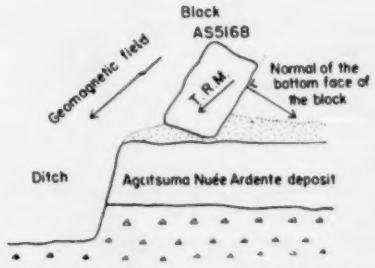

Fig. 10. Schematic diagram showing the relation between the orientations of the block (AS5168) of the Agatsuma Nuée Ardente deposit and its T.R.M.

area of the diagram very close to that of figures 4 and 5, namely, close to the direction of the geomagnetic field in 1783.

Someone might consider that the N.R.M. direction of the block (AS5168) had been fixed before it was thrown up by the Kambara Nuée Ardente and coincided by chance with that of the geomagnetic field when it fell on the ground. But this possibility can be precluded for the following reason. In the case of chance coincidence, the N.R.M. direction of the block should fall on the small circle whose center (p) represents the direction of the normal of the bottom face of the block (AS5168). The radius of the small circle is 49°, which is the sum of the complementary angle (47°) of the dip of N.R.M. (i.e. T.R.M.) of the Agatsuma Nuée Ardente deposit shown in figures 4 and 5 and the general dip (2°) of the land surface on which the block is now found. The former angle (47°), therefore, represents the angle between the normal of the bottom face and the N.R.M. direction of the block of the Agatsuma Nuée Ardente deposit. From figure 9, it is apparent that the points representing the N.R.M. direction of the bombs in the block (AS5168) do not fall on the small circle.

The conclusion that the block still maintained a temperature above the Curie point when it was thrown up by the Kambara Nuée Ardente implies that there was only a very short time interval between the eruptions of the Agatsuma and Kambara Nuées Ardentes.

CONCLUSION

The temperature of formation of pyroclastic deposits can thus be estimated from the N.R.M. direction of the deposit. If all the fragments in the deposit have a uniform orientation of their N.R.M., the temperature of its formation was higher than the Curie point of the constituent ferromagnetic minerals, provided the N.R.M. originated from the stable T.R.M. If the fragments show a random orientation of N.R.M., the temperature of deposition was lower than the Curie point. Examples of random orientation are found in the mud flow deposits, of uniform orientation in the pyroclastic flow deposits. The eruption date of two successive nuées ardentes in the 1783 activity of Asama Volcano has also been confirmed by the N.R.M. measurement.

REFERENCES

Akimoto, S., 1955, Magnetic properties of ferromagnetic minerals contained in igneous rocks: Japanese Journal Geophysics, v. 1, no. 2, p. 1-31.

Aramaki, S., 1956, The 1783 activity of Asama Volcano, Part I: Japanese Jour. Geology Geography, v. 27, p. 189-229.

————, 1957, The 1783 activity of Asama Volcano, Part II: Japanese Jour. Geology Geography, v. 28 (in press).

Kuno, H., 1950, Geology of Hakone Volcano and adjacent areas: Part I: Jour. Faculty Science, Univ. Tokyo, sec. II, v. 7, p. 257-279.

————, 1952, Explanatory text of the geologic map 'Atami' (in Japanese): Kawasaki-shi, Japan, Geol. Survey of Japan.

Lacroix, A., 1904, La montagne Pelée et ses éruptions: Paris, Masson et Cie.

Nagata, T., 1943, The natural remanent magnetism of volcanic rocks and its relation to geomagnetic phenomenon: Earthquake Research Inst. Bull., v. 21, p. 1-196.

————, 1954, Special report on palaeomagnetism: I. U. G. G. Xth Assembly, Rome.

Sekiya, S. and Kikuchi, Y., 1890, The eruption of Bandai-san: Jour. College Science, Imperial Univ. Japan, v. 3, p. 91-172.

Tsuya, H., 1940, Geological and petrological studies of Volcano Huzi (Fuji), III. 3. Geology of the southwestern foot of Volcano Huzi (in Japanese): Earthquake Research Inst. Bull., v. 18, p. 419-445.

Wentworth, C. K., and Williams, H., 1932, The classification and terminology of the pyroclastic rocks: National Research Council Bull., no. 89, p. 43-53.

Geological Institute
University of Tokyo
Tokyo, Japan

Geophysical Institute
University of Tokyo
Tokyo, Japan

[American Journal of Science, Vol. 255, November 1957, P. 628-640]

EXPERMENTAL DETERMINATION OF KYANITE-SILLIMANITE EQUILIBRIUM RELATIONS AT HIGH TEMPERATURES AND PRESSURES*

SYDNEY P. CLARK, Jr., EUGENE C. ROBERTSON, and FRANCIS BIRCH

ABSTRACT. The equilibrium curve between kyanite and sillimanite has been found to lie at 18,200 bars at 1000°C and 21,000 bars at 1300°C; the kyanite field lies on the high-pressure side of this curve. Kyanite and sillimanite could not be synthesized consistently below 1000°C, and it proved necessary to extrapolate the equilibrium curve to the lower temperatures encountered in regional metamorphism. Thermochemical data suggest that a curvilinear extrapolation is required, although curvature is not demanded by the experimental points. It is concluded that the assemblage quartz plus corundum, which was formed in most of the runs, is metastable under all conditions investigated.

The results demonstrate conclusively that kyanite can be formed in the absence of shearing stress. They also suggest that horizontal gradients of temperature, pressure, or both are required to account for the distribution of kyanite and sillimanite observed in regionally metamorphosed rocks.

INTRODUCTION

Knowledge of the physical conditions existing during their formation is essential to the understanding of metamorphic and igneous rocks. Once the fields of stability of their constituent minerals are known, the possible pressures and temperatures of formation of these rocks can be inferred. The simplest diagrams of mineral stability are those depicting polymorphism in a one-component system, and two very important polymorphs in metamorphic rocks are the aluminosilicates, kyanite and sillimanite. Analyses of these minerals show that the composition of each is remarkably close to Al_2SiO_5.

The results of 55 quenching runs, made in the enlarged version of Bridgman's 30,000-bar apparatus described by Robertson, Birch, and MacDonald (1957), are reported here. Most of the data apply to that portion of the kyanite-sillimanite boundary between pressures of 18,000 and 23,000 bars and at temperatures between 1000 and 1300°C.

APPARATUS AND PROCEDURE

The apparatus is described by Robertson et al. (1957), and only recent modifications will be considered in detail here. The pressure vessel is a tapered cylinder, forced into a conical hole in supporting rings by a hydraulic ram. The pressure is generated inside the cylinder by a piston advanced by an opposing hydraulic ram. The pressure medium is nitrogen.

Charges are held in gold or platinum capsules and are heated by a furnace inside the pressure vessel. The furnace is supported in a steel or copper tube, and it plugs into insulated electrical connections at the bottom of the pressure vessel. For temperatures up to 1000°C, the furnace is wound of kanthal wire on a porcelain tube, one-quarter inch inside diameter. For higher temperatures, the winding is of platinum-10 percent rhodium wire, and the core is an alundum tube, one-eighth inch inside diameter. The use of a smaller furnace at higher temperatures prevents overheating of the inner wall of the

* Paper No. 153 published under the auspices of the Committee on Experimental Geology and Geophysics and the Division of Geological Sciences at Harvard University.

pressure vessel, and also reduces the power required to reach high temperatures. The winding is about 3 inches long and is insulated by a closely fitting sleeve of massive pyrophyllite, marketed by the American Lava Corp. under the name "Lava".

Considerable difficulty is encountered with thermal gradients in these small furnaces. One of the main sources of trouble is convection of nitrogen through the furnace, which is mounted in a vertical position. Gradients due to the flow of nitrogen are markedly reduced by making the metal furnace sleeve gas-tight at the top, and by filling all open spaces within the furnace and between the furnace and the Lava sleeve with refractory material.

Near the ends of the furnace winding, gradients of the order of 1000°C/inch are inevitable, and the region of essentially uniform temperature in the center of the furnace is extremely short. The windings are more closely spaced near the ends of the furnace than opposite the charges, but steep gradients near the central part of the furnace have persisted. The gradient is reduced to about ten degrees in the length of the charge by placing the capsules in a heavy block of metal. The number of capsules is reduced when the metal block is used, but the more uniform temperature compensates for this sacrifice.

Five insulated leads, accommodating the various electrical circuits, are let into the pressure vessel through the plug at its bottom. The stem of the bottom plug is necessarily rather large, and its seal has not been wholly satisfactory. Leaks at this point terminated many of the runs. An unsupported area packing with five insulated leads has been tried recently; it has eliminated difficulties at pressures up to 20,000 bars.

Temperature is measured with platinum-platinum 10 percent rhodium thermocouples placed at each end of the capsules containing the charges. The cold junction of the thermocouples is in an ice bath outside the pressure vessel. Each thermocouple lead consists entirely of thermocouple wire except for a distance of three-sixteenth inches, which is in a hardened steel cone forming the pressure-tight seal. The mean thermal gradient in the bottom plug is measured by thermocouples at each end. It has never exceeded 15°C/inch, and hence the error introduced by the cones can hardly exceed 3°C. This small correction and the correction for the effect of pressure on the emf of the thermocouples have been neglected in the results.

Pressure is measured with a manganin coil calibrated against the freezing point of mercury at 0°C. The coil has a resistance of about 51 ohms, and its change of resistance is measured on a Carey-Foster bridge with a precision equivalent to about 20 bars. The coil is mounted on the bottom plug, between leads of thermocouple wire. Measurement of the thermal emf in this circuit gives the mean temperature of the coil. In this position its mean temperature has never exceeded 50°C; the correction to the measured pressure is less than 100 bars at this temperature (Robertson et al., 1957).

In making a run, the pressure is first raised to about 2,000 bars below the desired value, and the furnace is then heated to the desired temperature. The temperature is raised relatively slowly (about 100°C per minute) to reduce thermal shock in the apparatus and to guard against the development of

local hot spots in the furnace winding. After the furnace has reached temperature, the pressure is adjusted if necessary.

The charges are quenched by turning off the power to the furnace. The temperature drops below 300°C in 30 seconds and reaches about 100°C in one minute. The pressure is then released.

In the early stages of this work, the duration of runs was limited to about three hours by persistent small leaks and burning out of furnaces. Many of these difficulties have gradually been eliminated, and considerably longer runs are now feasible.

Starting materials tried in the synthesis of kyanite and sillimanite were kyanite from Gorham, Me., sillimanite from near Mt. Monadnook, N. H., andalusite from Laws, Calif., kaolinite from Murfreesboro, Ark., and synthetic gibbsite from the Norton Co. Capsules containing the charges were left unsealed, so that any water present could escape freely. In most of the successful runs the starting material was andalusite, kaolinite, or a mixture of kaolinite and gibbsite. Analyses of the andalusite and kaolinite are given in table 1.

TABLE 1

Chemical Analyses of Andalusite and Kaolinite

	J. Ito, Analyst	
	(1)	(2)
SiO_2	34.92	44.56
TiO_2	0.63	0.49
Al_2O_3	59.61	39.40
Total Fe as Fe_2O_3	0.66	0.47
MnO	0.00	0.00
MgO	0.00	0.10
CaO	0.28	0.73
Na_2O	0.10	0.09
K_2O	0.13	0.10
H_2O	3.71	14.47
	100.04	100.41
	Traces of Ga, Cu, Au.	Traces of Ga, Cu, Zr.
Mole fractions		
SiO_2	582	743
Al_2O_3	584	386

(1) Andalusite, White Mts., near Laws, Calif. Harvard Museum #95769.
(2) Kaolinite, Murfreesboro, Ark. Harvard Museum #102649.

In some of the runs, kaolinite and gibbsite were mixed to give a 1:1 ratio of Al_2O_3 and SiO_2, but it was thought that dehydration of the gibbsite favored nucleation of corrundum and was partially responsible for the appearance of metastable quartz plus corundum. In later runs, kaolinite alone was used as a starting material; it reacts to form an aluminosilicate plus quartz, but since both kyanite and sillimanite are stable with quartz, this has no effect on the equilibrium curve.

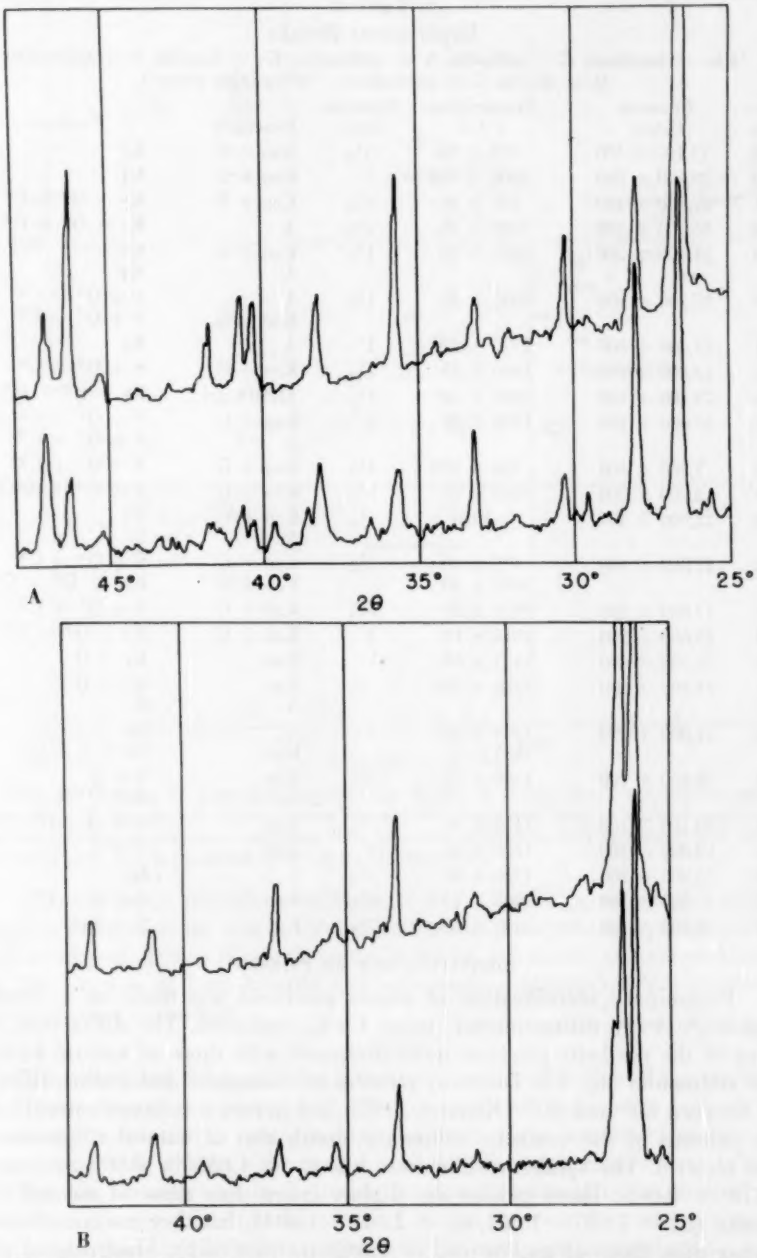

Fig. 1. X-ray diffraction patterns of natural and synthetic kyanite and sillimanite (Cu-K_α radiation). A: upper curve—natural kyanite; lower curve—synthetic kyanite. B: upper curve—natural sillimanite; lower curve—synthetic sillimanite.

TABLE 2

Experiments Results

(Kao = kaolinite, G = gibbsite, A = andalusite, Ky = kyanite, S = sillimanite, Q = quartz, C = corundum. *Metastable phase.)

Run No.	Pressure (bars)	Temperature (°C.)	Duration (hrs.)	Reactants	Products
38	19,100 ± 100	975 ± 25	1½	Kao + G	Ky
40	18,600 ± 500	1000 ± 100	1	Kao + G	Ky
41	21,200 ± 100	910 ± 90	1¼	Kao + G	Ky + Q* + C*
44	18,900 ± 300	1000 ± 25	1½	A	Ky + Q* + C*
48	21,400 ± 200	1035 ± 20	1¾	Kao + G	Ky
				A	Ky
49	12,100 ± 100	1045 ± 30	1½	A	S + Q* + C*
				Kao + G	S + Q* + C*
51	24,400 ± 300	1320 ± 20	1	A	Ky
53	12,500 ± 100	1050 ± 25	1¼	Kao + G	S + Q* + C*
66	23,400 ± 100	1080 ± 50	1¼	Al_2SiO_5 gel	Ky + Q* + C*
78	16,000 ± 100	1100 ± 20	1	Kao + G	S + Q* + C*
				A	S + Q* + C*
79	7,500 ± 100	750 ± 100	1½	Kao + G	S + Q* + C*
85	12,200 ± 200	845 ± 20	3¼	Kao + G	S + Q* + C*
88	22,600 ± 400	>1280	¼	Kao + G	Ky
				A	S
90	17,000 ± 100	975 ± 30	2¾	Kao + G	S + Q* + C*
		1055 ± 30		Kao + G	Ky* + Q* + C*
91	17,000 ± 100	1020 ± 20	3¼	Kao + G	S + Q* + C*
93	18,600 ± 200	1015 ± 10	3	Kao + G	Ky + Q* + C*
95	22,900 ± 400	1325 ± 50	1	Kao	Ky + Q
101	21,800 ± 100	1250 ± 200	½	Kao	Ky + Q
				A	S
106	21,000 ± 100	1245 ± 30	1	A	Ky
		1305 ± 30		Kao	Ky + S + Q
112	19,600 ± 100	1260 ± 25	1½	Kao	S + Q
				A	S + Q* + C*
115	18,100 ± 100	1110 ± 30	½	Kao	S + Q + C*
117	19,000 ± 100	1105 ± 15	3	Kao	S + Q
120	23,900 ± 200	1220 ± 50	2¾	S	Ky
127	17,700 ± 100	995 ± 10	6½	Kao	S + Q + C*
128	18,600 ± 100	1340 ± 30	7¾	Ky	S + Ky*

IDENTIFICATION OF PHASES

Preliminary identification of phases produced was made on a Norelco high-angle x-ray diffractometer, using Cu-K_α radiation. The diffraction patterns of the synthetic products were compared with those of natural kyanite and sillimanite (fig. 1). The x-ray patterns of sillimanite and mullite differ in 2θ between 50° and 60° (Kennedy, 1955 and personal communication), and the patterns of the synthetic sillimanite match that of natural sillimanite in this interval. The synthetic sillimanite has $n_\alpha = 1.655 \pm 0.005$ and $n_\gamma = 1.675 \pm 0.005$. These indices are slightly lower than those of natural sillimanite ($n_\alpha = 1.657 - 1.661$, $n_\gamma = 1.677 - 1.684$), but they are considerably higher than those of mullite ($n_\alpha = 1.642$, $n_\gamma = 1.654$). Most natural sillimanite contains a small amount of iron, and this may account for the higher indices.

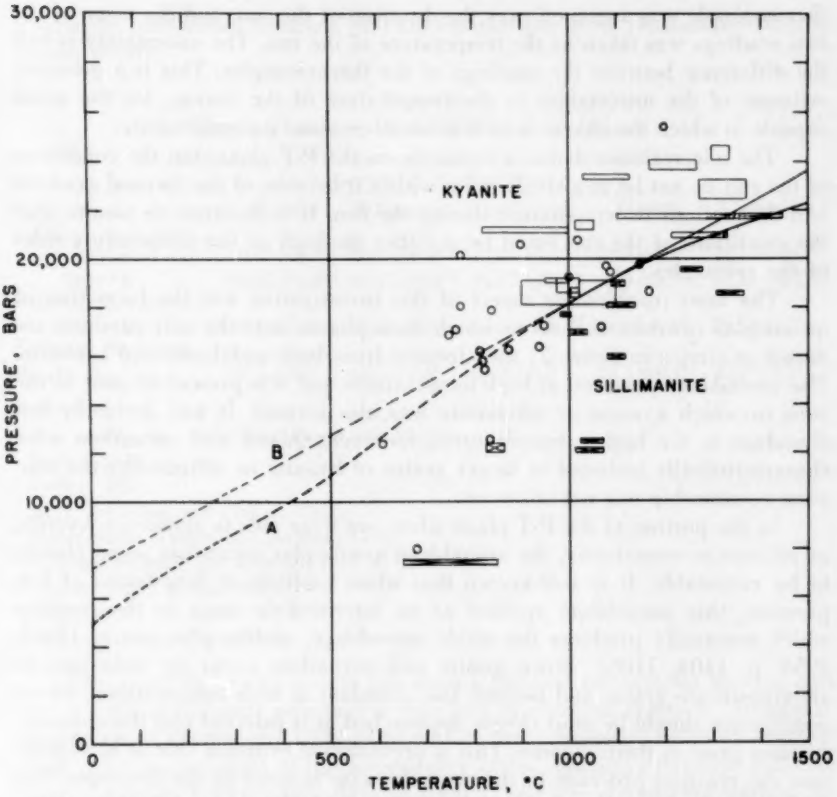

Fig. 2. Results of quenching experiments. Curve A is the "best" equilibrium curve. Curve B is a straight line extrapolation. Open boxes represent runs in which kyanite was produced, boxes with crosses represent runs in which sillimanite was produced, and circles represent runs which produced only quartz + corundum.

The synthetic crystals of sillimanite have the shape of stubby prisms, elongate parallel to the *c*-axis. Crystal outlines of the synthetic kyanite are less well-developed; it has the same mean index of refraction as natural kyanite (1.72). Crystals of both kyanite and sillimanite contain abundant inclusions of quartz and corundum.

RESULTS

The results of the quenching runs are given in table 2, and the positions of the runs are shown in figure 2. The uncertainties in pressure indicate the maximum fluctuation in pressure during the run. No uncertainty less than 100 bars is reported; although the precision of the pressure measurements is higher than this, uncertainties in the correction for the temperature of the coil and imperfect compensation for the effect of temperature on the resistance of the leads make this a more realistic estimate of the minimum uncertainty.

The uncertainties in temperature are determined by readings of the thermocouples at the ends of the capsules. The temperature recorded by each

thermocouple was averaged over the duration of the run, and the mean of the two readings was taken as the temperature of the run. The uncertainty is half the difference between the readings of the thermocouples. This is a generous estimate of the uncertainty in the temperature of the charge, for the metal capsule in which the charge is held tends to even out its temperature.

The uncertainties define a rectangle on the P-T plane, but the conditions of the run do not lie at a single point within it because of the thermal gradient and fluctuations in temperature during the run. It is incorrect to assume that the conditions of the run could be at either the high or low-temperature sides of the rectangles.

The most troublesome aspect of this investigation was the formation of quartz plus corundum. Runs in which these phases were the only products are shown as circles in figure 2; they formed from both andalusite and kaolinite. The assemblage persisted at high temperatures and was present in most of the runs in which kyanite or sillimanite was also formed. It was decidedly less abundant at the higher temperatures, however. Quartz and corundum were characteristically included in larger grains of kyanite or sillimanite; the converse relationship was not observed.

In the portion of the P-T plane where we were able to synthesize kyanite or sillimanite consistently, the assemblage quartz plus corundum seems clearly to be metastable. It is well-known that when kaolinite is dehydrated at low pressure, this assemblage appears as an intermediate stage in the reaction which eventually produces the stable assemblage, mullite plus quartz (Eitel, 1954, p. 1104, 1106). Since quartz and corundum occur as inclusions in aluminosilicate grains and become less abundant at high temperatures, where equilibrium should be most closely approached, it is inferred that the aluminosilicates grow at their expense. This is presumptive evidence that at high pressure the reaction proceeds in the same stepwise manner as the decomposition of kaolinite at low pressure. Both andalusite and kaolinite gave similar results.

It is perhaps less clear that quartz plus corundum is a metastable assemblage below 1000°C, but this is inferred from the stepwise nature of the reaction. Our failure to form kyanite or sillimanite consistently below 1000°C is interpreted as due to the slow rate at which early-formed quartz and corundum react at these temperatures. There is no way in which our runs can be separated into well-defined fields of aluminosilicates and quartz plus corundum; on the other hand the fields of kyanite and sillimanite can be cleanly separated. The stability of quartz plus corundum can only be established by demonstrating that they can be formed reversibly from kyanite and sillimanite. Lacking such evidence, and faced with ample evidence of the reluctance with which quartz and corundum combine, we regard them as metastable in all of our runs.

This conclusion is consistent with the thermochemical data on these minerals (table 3). From these data we estimate that if the heat of formation of sillimanite from the oxides is algebraically less than –500 to –1000 cal/mol, quartz plus corundum is a metastable assemblage under all of the conditions we have investigated. The uncertainty in this estimate is probably a few kilocalories per mole. Calorimetric determinations of the heat of formation of

sillimanite give values of about –50 kilocalories per mole (Kubaschewski and Evans, 1956).

TABLE 3

Thermochemical Data Used in Calculations

The room-temperature data were taken from the compilation of Prof. Gordon J. F. MacDonald

	Kyanite	Sillimanite	Andalusite	Quartz	Corundum
Entropy, cal/mol°C.					
300 °K	20.02 ± 0.1[1]	22.97 ± 0.1[1]	22.28 ± 0.1[1]	10.0 ± 0.1[1]	12.16 ± 0.02[4]
1600 °K	90.85 ± 0.6[2,3]	92.17 ± 0.6[2,3]	94.27 ± 0.6[2,3]	35.9 ± 0.2[2,3]	57.53 ± 0.1[2,4]
Volume, cm³/mol.					
300 °K	43.3 ± 1.0[5]	49.0 ± 1.0[7]	51.6 ± 1.0[1]	22.6 ± 0.03[9]	25.5 ± 0.2[6]
Enthalpy, kcal/mol.					
$H_{1600\,°K} - H_{300\,°K}$	57.7 ± 0.6[2]	56.3 ± 0.6[2]	56.8 ± 0.6[2]	21.1 ± 0.1[2]	37.0 ± 0.1[2]

References.

[1] Hey and Taylor, 1931; MacDonald and Merriam, 1938.
[2] Kelley, 1949.
[3] Kelley, 1950.
[4] Kerr, Johnston, and Hallett, 1950.
[5] Naray-Szabo, Taylor, and Jackson, 1929.
[6] Palache, Berman, and Frondel, 1944.
[7] Taylor, 1928; Taylor, 1929.
[8] Todd, 1950.
[9] Wyckoff, 1926; Gibbs, 1926.

The minerals in this system are among the best refractories known, and they are extraordinarily reluctant to take part in chemical reaction. Metastable persistence of kyanite and sillimanite outside their respective fields of stability made the demonstration of the reversibility of the reaction extremely difficult. Natural kyanite held for four days at 1000°C and one atmosphere showed no sign of reaction; this run is 18,000 bars below the equilibrium curve. The reaction was reversed at higher temperature. Synthetic sillimanite produced in run 88 was completely converted to kyanite at 1220°C and 23,900 bars. Natural kyanite, after grinding for 60 hours, was converted to a mixture of kyanite and sillimanite at 18,600 bars and 1340°C. The reaction was thus reversed at points about 3000 bars from the equilibrium curve. This is the maximum uncertainty in its position.

Metastable formation of kyanite or sillimanite in the field of the other is known to have occurred only in run 90 (table 2). Subsequent runs showed that the kyanite formed in this run was metastable, and it is not shown in figure 2.

The preliminary results published by Griggs and Kennedy (1956) show an equilibrium curve between kyanite and sillimanite which lies at slightly over 20,000 bars at 1000°C; our curve lies at 18,000 bars at the same temperature.

EXTRAPOLATION OF THE EQUILIBRIUM CURVE TO LOWER TEMPERATURES

The equilibrium curve between kyanite and sillimanite is located between 1000°C and 1300°C by this work. These temperatures are too high for im-

mediate geological application, and it is desirable to extrapolate the curve to lower temperatures. High-temperature heat capacity data (Kelley, 1949) show that ΔS, the entropy change of the reaction, depends on temperature at one atmosphere; hence a curvilinear extrapolation is required. Differences in thermal expansion and compressibility of kyanite and sillimanite, $\Delta\alpha$ and $\Delta\beta$ respectively, will be neglected. This introduces only a small error insofar as these quantities affect ΔV, the volume change of the reaction. $\Delta\alpha$ is likely to be less than 10^{-5} deg^{-1}, and $\Delta\beta$ can hardly exceed 10^{-6} bars^{-1}. The correction to ΔV is thus unlikely to exceed 3 percent at the highest temperatures and pressures. But the entropy change of the reaction is dependent on $\Delta\alpha$ through the relation $(\partial\Delta S/\partial P)_T = -\Delta(V\alpha) = -\overline{V}\Delta\alpha$, where $\overline{V}$ is a mean volume. $\overline{V}$ is about 45 cm^3/mol, and with $\Delta\alpha$ assumed to be 10^{-5} deg^{-1}, we find that ΔS changes by about 9 dj (decijoules)/mol°C in 20,000 bars. This is about 8 percent of the entropy change at room temperature or 15 percent of the change at 1100°C.

The equilibrium curve is given by the equation

$$(1) \qquad P(T) = P(T_o) + (\Delta S/\Delta V)_o\,(T - T_o) + \frac{1}{\Delta V}\int_{T_o}^{T} \Delta S(T)\,dT$$

where $\Delta S(T)$ is chosen to vanish at $T = T_o$. $(\Delta S/\Delta V)_o$ and $P(T_o)$ are fixed by the equilibrium pressures at two temperatures. These were chosen to be 1300 and 1600°K. The integral in (1) was evaluated from the high-temperature entropy data given by Kelley (1949).

The non-linearity of the equilibrium curve is contained in the third term on the right of (1), and this term is subject to large uncertainties that do not affect the others. The high-temperature entropy data are estimated to be uncertain by about 20 dj. Random errors tend to cancel in the integration, but the integral is nevertheless subject to an uncertainty of perhaps 30 percent. Further errors are introduced by neglect of $\Delta\alpha$ and $\Delta\beta$. Finally, $\Delta V = 5.7 \pm 1.3$ cm^3/mol (table 3); the uncertainty in this factor is almost 25 percent. Combining these independent errors, we estimate the uncertainty in this term to be about 3,000 bars at 25°C and 1500 bars at 500°C.

Utilizing (1), curve A in figure 2 was extrapolated to room temperature; it was fitted to the experimental data between 1000°C and 1300°C by placing it about halfway between adjacent points in the kyanite and sillimanite fields. Curve B in figure 2 is a linear extrapolation.

TABLE 4

Parameters of the Equilibrium Curves at 25°C

Curve	Intercept (bars)	$\frac{dP}{dT}$ at 25 °C. (bars/°C)	ΔS at 25 °C. (dj/mol/°C)
"A"	5650	19 ± 5	108 ± 24
Steepest	3650	21 ± 5	119 ± 25
Flattest	7550	18 ± 5	100 ± 23
"B"	7600	11	63 ± 14
From Low-Temperature Heat Capacities (Todd, 1950)			123 ± 6

Intercepts are listed in table 4 for these curves and for the flattest and steepest curves which could be drawn, using (1), without conflicting with any of the runs. The extreme curves bracket the uncertainties in the experimental location of the equilibrium curve, but there is an additional uncertainty of 3,000 bars in the intercept as discussed above. All of the curves are metastable below the kyanite-sillimanite-andalusite triple point.

The entropy change of the reaction at 25°C, computed from the slopes with $\Delta V = 5.7$ cm^3/mol, is compared in table 4 with the ΔS found by Todd (1950) from low-temperature heat capacities. The difference between Todd's value and those calculated from the curvilinear extrapolations are less than the estimated uncertainties. Linear extrapolation leads to a serious discrepancy.

FIELDS OF ANDALUSITE AND MULLITE

Other stable assemblages in this system are andalusite and mullite plus quartz, neither of which was synthesized under the conditions described here. Mullite is stable at zero pressure and high temperature (Eitel, 1954, p. 691); mullite plus quartz is converted to sillimanite at a pressure of about 5,000 bars at 600°C (Kennedy, 1955). At higher temperatures this reaction takes place at pressures which are assumed to be moderate but which are unknown. Work on this transition is in progress in this laboratory.

Data on the location and shape of the andalusite field are in conflict. Andalusite, kyanite, and sillimanite have been found together in nature, for example at Goat Mountain, Idaho (Heitanen, 1956). This suggests that a triple point exists at a pressure and temperature realized in the earth. Roy (1954) synthesized andalusite at pressures below 1,000 bars. The molar volume of sillimanite appears to be definitely smaller than that of andalusite (Taylor, 1928, 1929), and hence pressure favors sillimanite. If sillimanite is also the high-temperature phase, the equilibrium curve between andalusite and sillimanite has a negative slope; this is compatible both with the existence of a triple point and with Roy's observations. But heat capacity data (Kelley, 1949; Todd, 1950) suggest that the ΔS of the reaction changes sign at about 100°C and that andalusite is the high-temperature phase above that temperature.

The ΔS of the reaction sillimanite = andalusite is small, and we believe that the above data can best be reconciled by neglecting the measurements of heat capacity. On this assumption, a tentative phase diagram of the composition Al_2SiO_5 has been constructed (fig. 3); the relation of the andalusite field to those of sillimanite and kyanite is qualitatively the same as that proposed by Miyashiro (1949) and Thompson (1955). The diagram is complicated by the intersection of the sillimanite-mullite plus quartz and andalusite-sillimanite equilibrium curves. The slopes of these curves are hypothetical, as are the locations of the triple points.

GEOLOGICAL APPLICATIONS

The chemical potential of water determines whether aluminosilicates can be formed in most rocks at low temperatures. Hydrous phases, rich in alumina, take their place in many cases (Thompson, 1955). Were the chemical potential of water to have its highest possible value, the assemblage andalusite plus

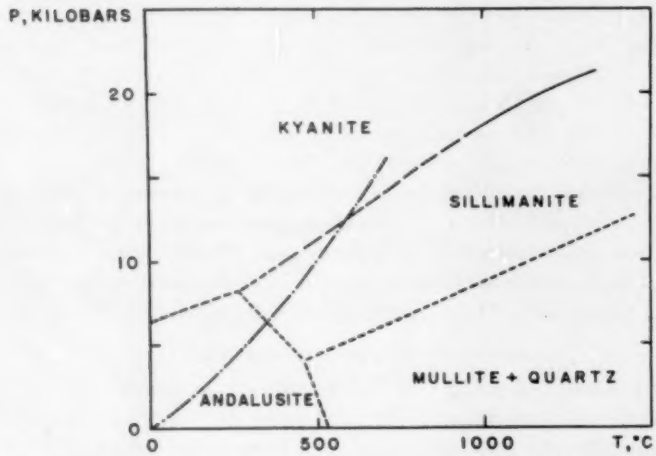

Fig. 3. Tentative phase diagram of the composition Al_2SiO_5. Phase boundaries indicated by short dashes are *not* experimentally determined, and no quantitative significance should be attached to them. The dot-dash curve indicates the *shape* of a typical geothermal gradient curve; its position has significance only at the origin.

quartz could not exist stably at pressures greater than a few hundred bars; pyrophyllite would appear in its place (Kennedy, 1955). We shall henceforth consider only cases in which either the temperature is sufficiently high or the chemical potential of water is sufficiently low so that one of the aluminosilicates may appear in the rock.

The stress mineral concept was introduced to account for the distribution in nature of kyanite, andalusite, and certain other minerals (Harker, 1939). The present work clearly demonstrates that kyanite can be formed in the absence of shear, but it is nevertheless a stress mineral in the sense that high pressures are necessary for its formation as a stable phase. The metastable prolongation of the steepest curve extrapolated by (1) intersects the pressure axis at 3,350 bars, and the stable boundary between the andalusite and kyanite fields must lie at higher pressures. Additional uncertainty in the extrapolated steepest curve is about 3,000 bars, but it is probable that kyanite is not stable under surface conditions.

A geothermal curve is superimposed on the phase diagram of the Al_2O_3-SiO_2 composition in figure 3. The gradient curve represents the pressures and temperatures that might be found in a vertical bore hole. In such a hole andalusite would be encountered in rocks of appropriate composition at shallow depths, and kyanite would appear at the greatest depths. Sillimanite would be found *above* kyanite if it appeared at all. This conclusion follows directly from the positive intercept of the kyanite-andalusite boundary; if the gradient curve is to enter the kyanite field at all, it must do so at elevated temperature and pressure.

Sillimanite-bearing rocks often occupy the central parts of regionally metamorphosed terrains, and kyanite occurs in rocks around the margin of the sillimanite zone. This spatial distribution of the aluminosilicates is observed

in New Hampshire and in the southeast Scottish Highlands. It would not be observed if the metamorphism resulted from deep burial in a region in which the geothermal gradient was everywhere the same and was "normal" in the sense that its curvature was as shown in figure 3. Horizontal gradients of temperature, pressure, or both during metamorphism are required to account for this distribution of kyanite and sillimanite. The existence of such horizontal gradients has previously been deduced from field studies (Harker, 1939, p. 185).

Field studies have revealed a "complete absence of cyanite from aureoles of thermal metamorphism" (Harker, 1939, p. 151), although sillimanite and andalusite are often found near the contacts of intrusive rocks. It appears that there is no known example of an igneous rock emplaced at suffiicently high pressure (and sufficiently low chemical potential of water) to make kyanite stable at the temperature prevailing in the wall rock. Once this temperature is better known, an upper limit to the pressure at which igneous rocks are known to solidify can be determined from the kyanite-sillimanite curve.

Syntectonic granites occurring in rocks in which kyanite had previously been formed through regional metamorphism are of special interest. Kyanite is never observed to persist up to the contacts, although sillimanite is characteristically present. This implies that a region of relatively high temperature or relatively low pressure existed near the contacts; the first alternative is a natural consequence of the emplacement of magma. The second alternative, which would be preferred by transformists, may require unlikely stress distributions.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the aid and advice of Prof. Gordon J. F. MacDonald. He helped with the laboratory work in the initial stages of this study and critically reviewed the manuscript. We have benefitted greatly from stimulating discussions of various aspects of this work with him, and with Prof. J. B. Thompson, Jr. and Dr. E-an Zen. Prof. George C. Kennedy kindly provided x-ray standards of sillimanite and mullite and kept us abreast of his own unpublished work in this system. Profs. C. S. Hurlbut, Jr. and Clifford Frondel supplied us with mineral specimens for use as reactants and as x-ray standards.

This work was supported in part by the Office of Naval Research.

REFERENCES

Eitel, Wilhelm, 1954, The physical chemistry of the silicates: Chicago, Univ. of Chicago Press.

Gibbs, R. E., 1926, Structure of α-quartz: Royal Soc. London Proc., Ser. A, v. 110, p. 443-455.

Griggs, D. T., and Kennedy, G. C., 1956, A simple apparatus for high pressures and temperatures: Am. Jour. Sci., v. 254, p. 722-735.

Harker, Alfred, 1939, Metamorphism: London, Methuen & Co. Ltd.

Heitanen, Anna, 1956, Kyanite, andalusite, and sillimanite in the schist in Boehls Butte Quadrangle, Idaho: Am. Mineralogist, v. 41, p. 1-27.

Hey, J. S., and Taylor, W. H., 1931, The coordination number of aluminum in the alumino-silicates: Zeits Krist., v. 80, p. 428-441.

Kelley, K. K., 1949, Contributions to the data on theoretical metallurgy. X. High-temperature heat-content, heat-capacity, and entropy data for inorganic compounds: U. S. Bur. Mines Bull. 476.

————, 1950, Contributions to the data on theoretical metallurgy. XI. Entropies of inorganic substances: U. S. Bur. Mines Bull. 477.

Kennedy, G. C., 1955, Pyrophyllite-sillimanite-mullite equilibrium relations to 20,000 bars and 800°C: Geol. Soc. America Bull., v. 66, p. 1584.

Kerr, E. G., Johnston, H. L., and Hallett, N., 1950, Low temperature heat capacities of inorganic solids. III. Heat capacity of aluminum oxide (synthetic sapphire) from 19° to 300° K: Am. Chem. Soc. Jour., v. 72, p. 4740-4742.

Kubaschewski, O., and Evans, E., 1956, Metallurgical thermochemistry: London, Pergamon Press.

MacDonald, G. A., and Merriam, R., 1938, Andalusite in pegmatite from Fresno County, California: Am. Mineralogist, v. 23, p. 588-594.

Miyashiro, Akiho, 1949, The stability relation of kyanite, sillimanite and andalusite, and the physical condition of metamorphic processes: Geol. Soc. Japan Jour., v. 55, p. 218-223.

Naray-Szabo, St., Taylor, W. H., and Jackson, W. W., 1929, The structure of cyanite: Zeits, Krist., v. 71, p. 117-130.

Palache, Charles, Berman, Harry, and Frondel, Clifford, 1944, Dana's system of mineralogy, vol. 1: New York, John Wiley & Sons.

Robertson, E. C., Birch, F., and MacDonald, G. J. F., 1957, Experimental determination of jadeite stability relations to 25,000 bars: Am. Jour. Sci., v. 255, p. 115-137.

Roy, D. M., 1954, Hydrothermal synthesis of andalusite: Am. Mineralogist, v. 39, p. 140-143.

Taylor, W. H., 1928, The structure of sillimanite and mullite: Zeits. Krist., v. 68, p. 503-143.

————, 1929, The structure of andalusite: Zeits. Krist., v. 71, p. 205-218.

Thompson, J. B., 1955, The thermodynamic basis for the mineral facies concept: Am. Jour. Sci., v. 253, p. 65-103.

Todd, S. S., 1950, Heat capacities at low temperatures and entropies at 298.16° K of andalusite, kyanite, and sillimanite: Am. Chem. Soc. Jour., v. 72, p. 4742-4747.

Wyckoff, R. W. G., 1926, The crystal structure of the high temperature (β) modification of quartz: Am. Jour. Sci., 5th ser., v. 11, p. 101-112.

Dunbar Laboratory
Harvard University
Cambridge, Mass.

U. S. Geological Survey
Acorn Building
Eastern Ave. & Newell Street
Silver Spring, Md.

[American Journal of Science, Vol. 255, November 1957, P. 641-649]

EARLY MIOCENE ENTELODONTS, TEXAS COASTAL PLAIN

JOHN ANDREW WILSON

ABSTRACT. The discovery of an upper jaw fragment of *Dinohyus hollandi*, large early Miocene entelodont, in the Oakville sandstone of Washington County, Texas, permits an accuracy of correlation with the High Plains early Miocene not heretofore possible. A lower jaw of the same species found near Oakhurst, San Jacinto County, Texas, permits eastward extension of the Garvin Gully biostratigraphic unit, previously found only in the Oakville sandstone, into the Fleming formation. A diagramatic section showing the relationship of Garvin Gully, Burkeville, and Cold Spring biostratigraphic units with the lithologic units is presented.

INTRODUCTION

The discovery of the lower jaw of a large *Dinohyus* in east Texas and a fragment of an upper jaw in central Texas permits more accurate dating of Texas Coastal Plain vertebrate biostratigraphic units and furnishes a tie with lower Miocene vertebrate faunas of the High Plains. The early discovery of vertebrate faunas in the High Plains and Intermontane Basins of western North America focused attention on the prolific fossil deposits of these areas, but only recently with the description of the Florida and Texas Coastal Plain forms (especially by White, 1942, and Quinn, 1955), are the southern faunas becoming known. Although significant differences in faunal composition occur between the northern and the southern provinces, the time relationships between the two sedimentary sections are becoming more firmly established. Some of the High Plains genera survive longer on the Coastal Plain and other genera appear earlier there. It is therefore gratifying to report the finding of a genus that confirms with much greater accuracy than heretofore possible the correlation of the Coastal Plain and the High Plains faunas.

The drawings were paid for by a grant from The University of Texas Research Institute.

PALEONTOLOGY

In May 1956 Mr. E. J. Tharp of Brenham, Texas, sent to the Bureau of Economic Geology of The University of Texas an upper jaw fragment which I have identified as *Dinohyus hollandi* Peterson. In June 1956 Mr. Tharp took the writer to the abandoned road-metal quarry in the Oakville sandstone from which the jaw fragment was collected by chiselling it from a block of sandstone; the pit where the specimen had been was still visible at the time of this visit. The quarry (fig. 1), located about 12 miles northeast of Brenham, Washington County, is in a cross-bedded sandstone approximately 10 feet above the contact of the Oakville sandstone and the Catahoula formation.

This upper jaw fragment of *Dinohyus hollandi* Peterson (B.E.G. no. 40223-1, fig. 2) is a fragment of a maxillary containing P4 and M1 and was collected from the Oakville formation; by its association with other typical mammals it is to be included as a member of the Garvin Gulley fauna (Quinn, 1955).

From the table of measurements it will be seen that both Texas specimens are larger than the type of *D. hollandi* as measured by Peterson (1909) and

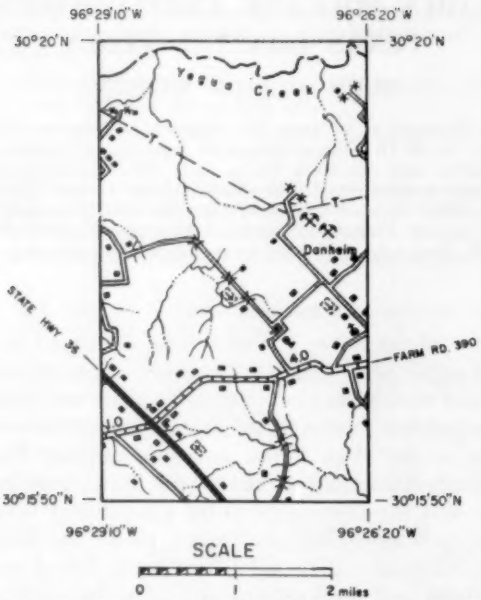

Fig. 1. A portion of Washington County, Texas, showing locality from which the upper jaw fragment of *Dinohyus hollandi*, B.E.G. no. 40223-1, was collected.

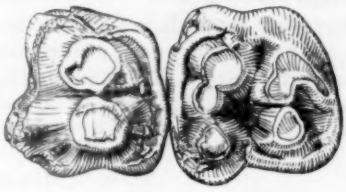

Fig. 2. *Dinohyus hollandi*, B.E.G. no. 40223-1, upper jaw fragment from Washington County, Texas. x1.

a mounted specimen of *D. hollandi*, University of Nebraska Museum no. 20-7-08, the measurements of which were kindly furnished me by Dr. E. H. Colbert of the American Museum of Natural History, New York. With a sample of such small size, it is impossible to attribute any significance to this variation. A comparison of the central Texas specimen with Peterson's (1909)

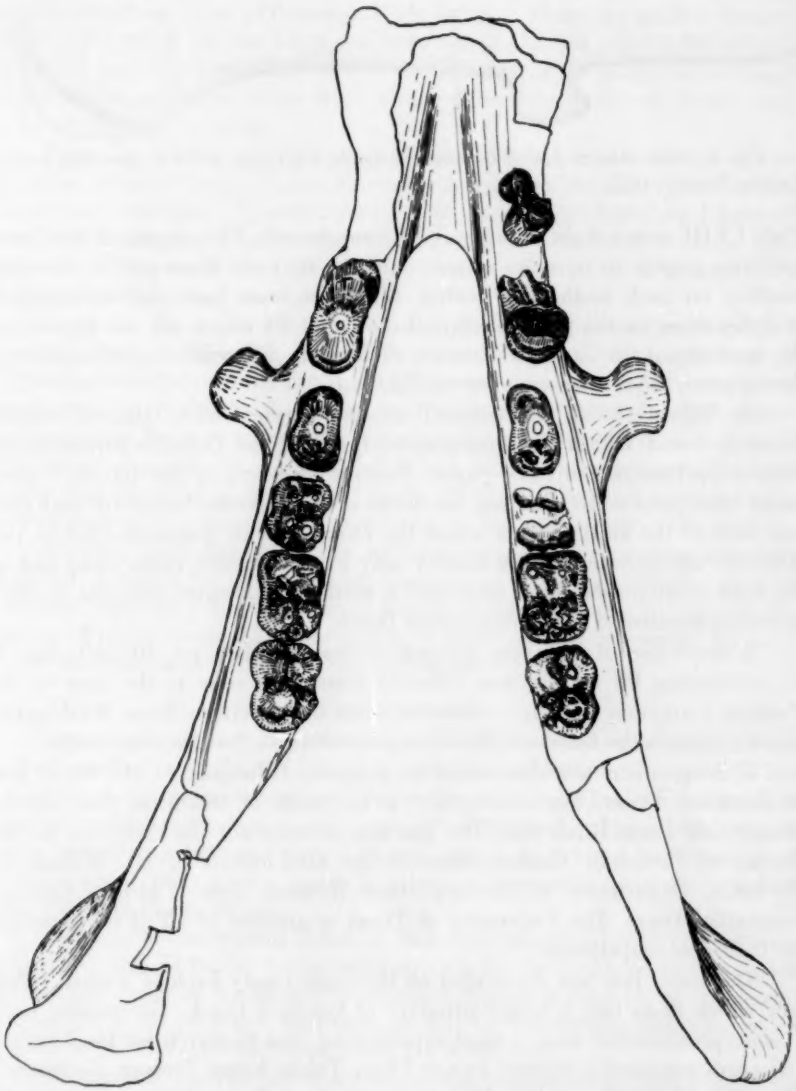

Fig. 3. Top view of *Dinohyus hollandi*, B.E.G. no. 40224-1, lower jaw from San Jacinto County, Texas. x0.5.

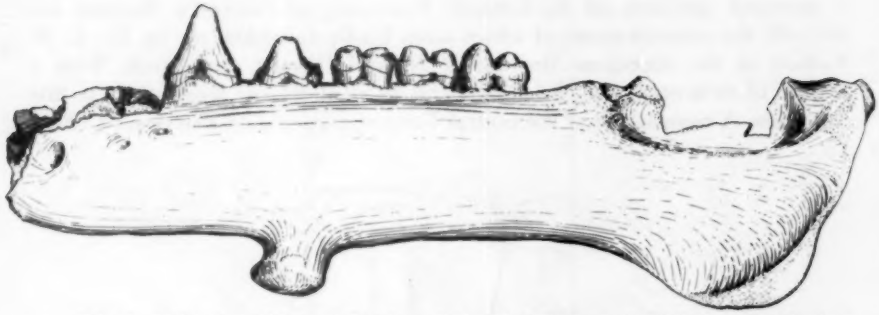

Fig. 4. Side view of jaw of *Dinohyus hollandi*, B.E.G. no. 40224-1, from San Jacinto County, Texas. x0.5.

Plate LVIII shows slight differences between the two. The cingula of the Texas specimen appear to be more robust, although they are developed in the same position on each tooth. The central Texas specimen has small mammillary protuberances on the postero-external corner of P4 which are not figured on the specimen at the Carnegie Museum. Other than differences in crown pattern due to wear, the crowns are very similar.

As Wilson (1956) has pointed out, the Garvin Gulley fauna in central Texas is found within the stratigraphic limits of the Oakville formation as revised by him in the same paper. Various members of the Garvin Gulley fauna have been collected along the strike of the Oakville formation both east and west of the locality from which the *Dinohyus* jaw fragment (B.E.G. no. 40223-1) was recovered. One locality only a few hundred yards away and at the same stratigraphic level contained a tooth of *Hippodon vellicans*, a characteristic member of the Garvin Gulley fauna.

A lower jaw of *Dinohyus hollandi* Peterson (B.E.G. no. 40224-1, figs. 3, 4), containing P3 to M3, was collected from beds close to the base of the Fleming formation and by correlation with the specimen from Washington County extends the Garvin Gulley fauna eastward to San Jacinto County.

This specimen was discovered on property belonging to Mr. O. B. Lee of Baytown, Texas; the locality is 3 miles north of Oakhurst, San Jacinto County, off Farm Road 946. The jaw was secured for the collection of the Bureau of Economic Geology through the kind efforts of Dr. Wilmot A. Thornton, Department of Zoology, Sam Houston State Teachers College, Huntsville, Texas. The University of Texas is grateful to all of these people for their fine cooperation.

The lower jaw was discovered on the right (east) bank of a small tributary which flows into a larger tributary of Carolina Creek. The locality is in a dense pine-wooded area, a most unpromising area to search for fossil bones. The small exposure is located on the Edgar Tobin Aerial Surveys photograph 7N—38E4, 2.7 inches east and 9.9 inches south of the northwest corner mark. The scale of the photograph is approximately 1 inch equals 1,000 feet.

Across the stream from where the lower jaw was found is a cut bank where fragments of turtle carapace, water-worn bone fragments, and reworked Cretaceous pelecypod shells were found.

Several differences between the type of *D. hollandi* and the San Jacinto County specimen are worthy of mention. Each of the molars on B.E.G. no. 40224-1 has a posterior heel which is well developed, like that shown in *Ammodon leidyanum* Marsh (Peterson, 1909, fig. 21). There is a greater diastema between $P\overline{3}$ and $P\overline{4}$ in the Texas specimen which also has a short diastema between $P\overline{4}$ and MI. These help to account for part of the difference in length of tooth row as shown in the table. Other differences in crown pattern seem to be attributable to wear.

To my knowledge only two other Miocene entelodonts have been reported from the Atlantic Coastal Plain: *Ammodon leidyanum* Marsh, 1893, from New Jersey and *Dinohyus* (?) *mento* Allen, 1926, from South Carolina. I have not been able to compare the Texas specimens with *D. mento*, but since the latter consists of little more than the symphisis of the lower jaw it is doubtful if this would be of value.

Casts of *Ammodon leidyanum* were kindly furnished by Dr. J. T. Gregory, Peabody Museum, Yale University. As one would expect, there are size differences between the two. Both $M\overline{3}$ in the Texas jaw are broader across the anterior cones than is *A. leidyanum*. The postero-external cingulum is more rugose on the Texas specimen. The hypoconid and entoconid in *A. leidyanum* are almost of equal size while in B.E.G. no. 40224-1 the hypoconid is much larger than the entoconid. The heel of the $P\overline{4}$ of *A. leidyanum* is more rugose and extends more posteriorly in proportion to the total length of the tooth.

Whether these differences are sufficient to warrant generic separation is doubtful. It seems the better course, however, to await the discovery of more complete material from New Jersey before deciding on the validity of *Ammodon*. Without comparative specimens of *Daeodon*, it is impossible for me to judge the taxonomic relationship of it to *Dinohyus*.

BIOSTRATIGRAPHY

More important than the recording of *Dinohyus* for the first time in Texas is the opportunity it affords for biostratigraphic correlation. This genus is best known from the Arikaree group of Nebraska, more specifically from the Harrison at the Agate Springs quarry near Agate, Nebraska. These beds are generally considered to be of late Arikareean age as defined by Wood et al. (1941). The Garvin Gulley fauna is therefore now more certainly correlated with the High Plains section.

The presence in central Texas of *Dinohyus* associated with typical members of the Garvin Gulley fauna certainly calls for the inclusion of this typical Arikareean genus as a member, uncommon though it may be, of the Garvin Gulley fauna. Its presence, therefore, in San Jacinto County indicates an extension of the Garvin Gulley fauna that far to the east.

Quinn (1955, p. 73) points out that *Synthetoceras rileyi* Frick from Aiken Hill, about 8 miles northeast of Huntsville, extends the Garvin Gulley fauna eastward as far as Walker County. A new locality, 1 mile east of Anderson,

Grimes County, on Farm Road 1773, produced an upper molar and an astragulus of *Hippodon vellicans*. This furnishes an intermediate locality of the Garvin Gulley fauna between Garvin Gulley proper and Aiken Hill. The San Jacinto County *Dinohyus* locality is the farthest east the Garvin Gulley fauna has been traced, but it is hoped that some day still more easterly localities will be found.

If *Ammodon leidyanum* is more advanced than *Dinohyus hollandi*, as Wood (1939) claims, there is the possibility that the Kirkwood formation of New Jersey is younger than the Oakville formation of Texas. A study of the diceratheres from Texas should help this problem of correlation, since two diceratheres are represented in the fauna of the Kirkwood.

The exact stratigraphic position of *Dinohyus mento* is unknown, but all lower Miocene formations in South Carolina are now placed in the Hawthorn formation (Cooke, 1936). This seems to agree reasonably well with correlations of White (1942).

STRATIGRAPHY

The nomenclature of the stratigraphic units of the Miocene in east Texas has been very confusing. Almost the only detailed geologic map of the area concerned is that of Dumble (1920). On this map the locality from which the *Dinohyus* lower jaw was recovered would fall very close to his contact between the Corrigan and Fleming formations. On the geologic map of Texas published by the U. S. Geological Survey in 1937, the area from which the lower jaw came is mapped as Lagarto clay. Following Stenzel, Turner, and Hesse (1944), Wilson (1956) has preferred to use Fleming formation instead of Lagarto clay. The contact of the Fleming formation and the Catahoula (roughly the Corrigan of Dumble) cannot be seen at the San Jacinto County locality; however, it can be safely assumed from the lithology of the beds at the locality that they are within the lower part of the Fleming formation. The lower jaw was taken from a lense of coarse, gray cross-bedded sand. The sand has a few pebbles of black rounded chert as well as reworked Cretaceous pelecypod shells and bone fragments. Above and below the sand lense is green calcareous clay, characteristic of the Fleming formation. The sand lense was evidently deposited in a stream channel within a back swamp environment.

With the single exception of the Aiken Hill locality in Walker County, all previously published Garvin Gulley fauna localities have been within the stratigraphic boundaries of the Oakville formation as defined by Wilson (1956). Using the U. S. Geological Survey 1937 Texas geologic map, there are now three Garvin Gulley fauna localities within the Fleming formation (Lagarto clay) east of the Brazos River. Parenthetically it should be mentioned that Garvin Gulley itself is east of the Brazos River, but the restriction of the Oakville formation to the area west of that river must certainly have been an expedient of map making, for it can easily be traced as a scarp-forming, mappable unit north of Navasota. Renick (1936) so traced the Oakville formation across Grimes County to the Walker County line; it has been his map, rather than the U. S. Geological Survey 1937 map, which has been used in figure 5 for the distribution of the Oakville formation.

Fig. 5.

Humble Oil & Refining Company geologists were reported by Ellisor (1944) to have traced the lower beds of the Fleming formation westward from the type locality. She reports this as follows (p. 1361):

> . . . . This basal zone of calcareous clays at the type locality [Fleming formation] in Tyler County can be traced across Polk, San Jacinto, and Walker counties into the lower Oakville as mapped in Grimes, Washington, Fayette, and Lavaca counties by Humble Oil and Refining Company geologists and by Coleman Renick [1936]. The sand member overlying these clays at the type locality is traceable westward from Tyler County across Polk, San Jacinto, and Walker counties into the cuesta-forming sandstone in Grimes, Washington, Fayette, and Lavaca counties, which Renick [1936] has called the Moulton sandstone at the base of his middle Oakville.

Since the maps referred to by Ellisor have never been published, it is impossible to determine where the sandstone occurs that contained the *Dinohyus* lower jaw; presumably it would be within the "basal zone of calcareous clays."

The mapping necessary to extend the Oakville formation eastward across Walker and San Jacinto counties is sometime in the future. For the present, therefore, it would seem best to include the Walker County site at Aiken Hill and the San Jacinto County site at Oakhurst (*Dinohyus* lower jaw) within the Fleming formation. This would then include within the presently known boundaries of the Fleming formation of Texas east of Grimes County, three biostratigraphic units. These are, from bottom to top, the Garvin Gulley fauna, the Burkeville fauna, and the Cold Spring fauna (Quinn 1955, and Wilson, 1956). The stratigraphic and biostratigraphic relations as currently visualized are diagrammatically pictured in figure 5.

TABLE 1

Comparative Measurements (in millimeters) of Three Specimens of *Dinohyus hollandi* Peterson

	From Peterson (1909, p. 80), presumably type, Carnegie Museum		Nebraska Museum no. 20-7-08	Texas specimens
Superior dentition				B.E.G. no. 40223-1
Antero-posterior diameter of P4	37		38	41.0
Transverse diameter of P4	40		44	45.5
Antero-posterior diameter of M1	42		43	45.8
Transverse diameter of M1	44		46	50.0
		Cast of		
Inferior dentition		Ammodom		B.E.G. no. 40224-1
Length of molar series	137	leidyanum	139	162
Antero-posterior diameter of P3	54		55	60.1
Transverse diameter of P3	28		29	31.8
Antero-posterior diameter of P4	45	52.9	46	55.0
Transverse diameter of P4	28	32.5	28	32.5
Antero-posterior diameter of M1	42		42	50.7
Transverse diameter of M1	34		34	38.1
Antero-posterior diameter of M2	47		49	55.0
Transverse diameter of M2	40		40	44.1
Antero-posterior diameter of M3	50	54.1	55	55.2
Transverse diameter of M3	39	40.7	40	44.8
Mandible				
Depth of mandible, inferior border of angle to and including condyle	200		205	180
Depth of mandible at M3	120		114	117
Depth of mandible at P2	100		111	118

CONCLUSIONS

Dinohyus hollandi Peterson is present in the Oakville formation of Washington County, Texas, and permits correlation with the Arikareean of the Great Plains. The same species in San Jacinto County extends the Garvin Gulley fauna eastward beyond the present mapped area of the Oakville formation into the lower part of the Fleming formation.

REFERENCES

Allen, G. M., 1926, Fossil mammals from South Carolina: Mus. Comp. Zool. Harvard College Bull., v. 67, no. 14, p. 447-467.

Cooke, C. W., 1936, Geology of the coastal plain of South Carolina: U. S. Geol. Survey Bull. 867, 196 p.

Dumble, E. T., 1920, The Geology of East Texas: Univ. Texas Bull. 1869 (Dec. 10, 1918), 388 p.

Ellisor, A. C., 1944, Anahuac formation: Amer. Assoc. Petrol. Geol. Bull., v. 28, p. 1355-1375.

Marsh, O. C., 1893, Description of Miocene Mammalia: Am. Jour. Sci., 3d ser., v. 46, no. 275, p. 407-412.

Peterson, O. A., 1909, A revision of the entelodonts: Carnegie Mus. Mem., v. 4, p. 41-158.

Quinn, J. H., 1955, Miocene Equidae of the Texas Gulf Coastal Plain: Univ. Texas Pub. 5516, 102 p.

Renick, B. C., 1936, The Jackson group and the Catahoula and Oakville formations in a part of the Texas Gulf coastal plain: Univ. Texas Bull. 3619, 104 p.

Stenzel, H. B., Turner, F. E., and Hesse, C. J., 1944, Brackish and non-marine Miocene in southeastern Texas: Amer. Assoc. Petrol. Geol. Bull., v. 28, p. 977-1011.

White, T. E., 1942, The Lower Miocene Mammal Fauna of Florida: Mus. Comp. Zool. Harvard College Bull., v. 92, no. 1, 49 p.

Wilson, J. A., 1956, Miocene formations and vertebrate biostratigraphic units, Texas coastal plain: Amer. Assoc. Petrol. Geol. Bull., v. 40, p. 2233-2246.

Wood, H. E., 1939, Lower Miocene Land Mammals of New Jersey: (Abst.) Geol. Soc. America Bull., v. 50, p. 1968-1969.

Wood, H. E., *et al.*, 1941, Nomenclature and correlation of the North American continental Tertiary: Geol. Soc. America Bull., v. 52, p. 48.

Department of Geology
University of Texas
Austin, Texas

[American Journal of Science, Vol. 255, November 1957, P. 650-655]

COMBINATION TWINNING IN PLAGIOCLASE FELSPARS

J. V. ROSS

ABSTRACT. In many igneous rocks, the concentric zoning of the individuals shows that small plagioclase crystals have combined to form large aggregates of crystals. Crystals combine along smooth composition planes, normally (010), and their combination is governed by either the Carlsbad, the Albite-Carlsbad, or the Albite-Ala law. Combination of plagioclase crystals, as described, is believed to be characteristic of truly magmatic rocks, and thus may be a useful criterion for separating magmatic from metamorphic or metasomatic rocks.

INTRODUCTION

The present study originated from a suggestion by Dr. W. H. Mathews, who, while describing a series of volcanic rocks from the Garibaldi region of British Columbia, noticed that many of the plagioclase felspars within the lavas occurred as aggregates of crystals, and that many of the individuals comprising these aggregates were in twin relationships. These crystals are distinguished by distinct nuclei outlined by concentric zones, with outer-zones encompassing all parts of the aggregate, by smooth composition planes, and by zig-zag outlines. It was therefore decided to investigate crystal associations of this type to see if they are the result of simple crystallization, or whether they result from the combination of two or more crystals after crystallization, and what laws govern these combinations.

Literature describing previous work related to the twinning and optics of plagioclase felspars is extensive, but very few data dealing with post-crystallization combination and parallel growth of plagioclase have been recorded. Hence, it is thought that a statement concerning the nature and possible petrological significance of combination and parallel growth in plagioclase felspars should be placed on record.

SOURCE OF MATERIAL

Since the study required rocks with many crystals of plagioclase felspar, a suite of porphyritic volcanic rocks from the Garibaldi area, western British Columbia, was taken, and the characters of the plagioclase felspars compared with those belonging to a suite of granitic rocks from the Caulfeild, Vancouver area of the Coast Range Batholith.

UNIVERSAL-STAGE MEASUREMENTS

The observations and measurements of the plagioclase felspars in the various rocks studied were made with the Leitz 4-axis stage[1]. Aggregates, of all sizes, of plagioclase crystals, were examined, and in each combination of crystals the composition plane between the crystals was identified, and the twin law relating the crystals was determined by the method and diagrams shown by Turner (1947).

[1] Index of hemisphere used was 1.516, and that of the immersion liquid was 1.519 at 18°C. The observations with the universal-stage and the plotting of same on a Wulff's net were carried out simultaneously. The twin laws and compositions of the plagioclase felspars were determined according to Turner's (1947) methods and diagrams, and checked by v.d. Kaaden's (1951) curves.

A). *The Garibaldi volcanics*—are a suite of rocks that range in composition from basalt through andesite to dacite, the two latter types forming the bulk of the rocks seen; they have been described by W. H. Mathews (1948). All the rocks are porphyritic, with concentrically zoned phenocrysts of plagioclase felspars varying in size from one to three millimeters in length, set in a groundmass of fine-grained microlites of zoned plagioclase that rarely attain a size of one millimeter, and they commonly exhibit flow structure.

Combinations of crystals of plagioclase have been observed in both the phenocrysts and groundmass plagioclase; the term combination being used here to denote a coalescence of two, three, or four concentrically zoned individuals, as shown in figure 1. Some hundred and fifty-five of these combinations have been noted and the optic and crystallographic relations between individuals within the combinations determined. In all instances individuals within a combination are related by some common twin relationship, and in the majority of relations the plane joining two individuals is (010). However, although the composition plane of two individuals is relatively constant, the twin axis relating individuals varies considerably. From the readings shown in table 1 it will be seen that three twin axes are common, namely, [001], $\perp$ [001]/(010), and $\perp$ [100]/(010), and since the composi-

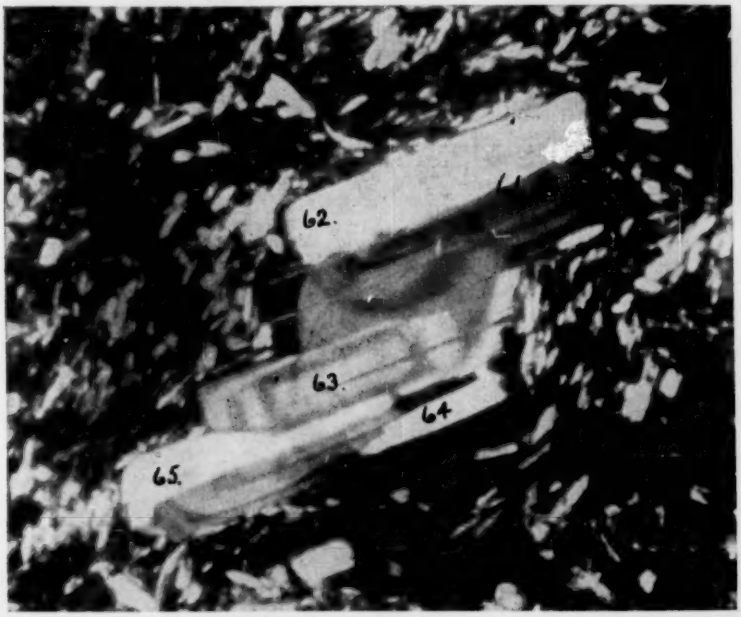

Fig. 1. Porphyritic plagioclase aggregation.
62:61—Carlsbad.
61:63—Albite.
63:64—Albite-Carlsbad.
63:65—Carlsbad.
Crossed nicols. x 60. Andesite, Garibaldi.

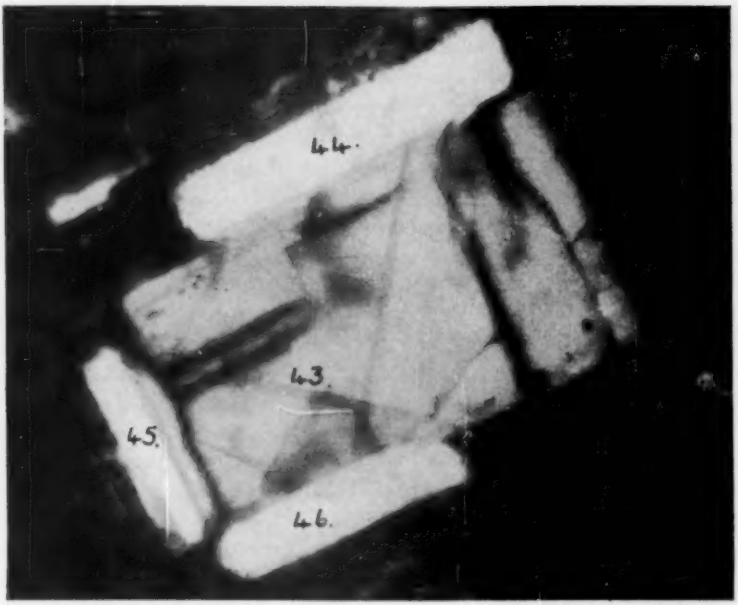

Fig. 2. Combination of phenocryst plagioclase with groundmass microlites.
43:44—Albite-Carlsbad.
43:45—Ala-A.
43:46—Carlsbad.
Crossed nicols. x 225. Andesite, Garibaldi.

tion plane for two individuals is in nearly every example always (010), the twin laws governing the combinations are therefore Carlsbad, Albite-Carlsbad, and Albite-Ala.

Tables 1 and 2 refer to the Garibaldi volcanics and show the frequency of twin types developed within the combinations examined in the phenocryst and groundmass plagioclase. From these tables it would appear that the most common type of twin law governing the combination of plagioclase felspars is Albite-Carlsbad, in both the groundmass and phenocrysts. However, there are exceptions to this rule.

TABLE 1

T.A.	[001]	⊥[001]/(010)	⊥[100]/(010)	Total
C.P.	(010) 31	53	19	103

Table showing the variation of twin laws governing the combination of phenocryst plagioclase felspars within the Garibaldi volcanics.

TABLE 2

T.A.	[001]	⊥[001]/(010)	⊥[100]/(010)	Total
C.P.	(010) 6	37	9	52

Table showing the variation of twin laws governing the combination of groundmass plagioclase felspars within the Garibaldi volcanics.

In some instances it has been observed that first generation phenocrysts have combined with second generation microlites, and in this latter case the plane

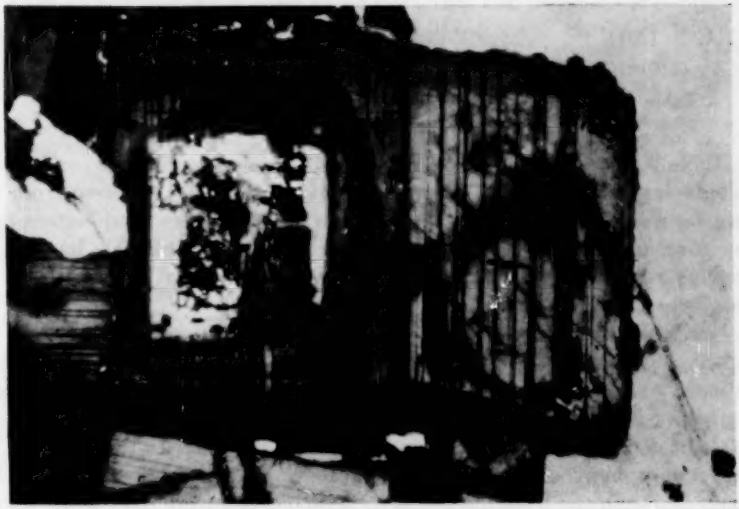

Fig. 3. Shows combination of plagioclase crystals.
161:162—Carlsbad.
Small, dark border encloses the combination twin, which is followed by a small zone of acid plagioclase. The formation of this combination twin took place before the formation of this reaction zone.
Crossed nicols. x 60. Diorite, Caulfeild.

joining the individuals is either (001) or (010), as shown in figure 2. Under these conditions of combination the twin axes are $\perp$ [001]/(010) and [100], so that the twin laws governing the combinations are Albite-Carlsbad and Ala-A, with the former being the dominant type of combination.

B). *The Caulfeild Quartz Diorite*—is a reasonably coarse-grained rock with crystals ranging in size from two to four millimeters. It consists almost wholly of plagioclase and hornblende, the former constituting about sixty-five percent of the rock. A small amount of quartz and some biotite are the other primary constituents, with some accessory sphene and magnetite. The plagioclase is commonly strongly zoned with the composition varying from basic andesine up to albite.

Combinations of two or more plagioclase felspars have been observed within these dioritic rocks, but their frequency of occurrence is relatively small when compared with that of combinations in the Garibaldi volcanics. Only twenty-four combinations of plagioclase felspars have been observed from approximately the same number of thin sections as were available for the Garibaldi volcanics. In all instances the composition plane for each composition is (010), and the twin axes determined are [001], $\perp$ [001]/(010), and $\perp$ [100]/(010). The twin laws governing the combinations of the plagioclase felspars are therefore Carlsbad, Albite-Carlsbad, and Albite-Ala. These are the same twin laws as were determined for the volcanic rocks, and their numerical occurrences are shown in table 3.

TABLE 3

T.A.	[001]	⊥[001]/(010)	⊥[100]/(010)	Total
C.P.	(010) 12	7	5	24

Table showing the variation of twin laws governing the combination of plagioclase felspars within the Caulfeild Quartz Diorite.

Table 3 shows that the frequency of twin laws governing the combination of plagioclase felspars in the Caulfeild rocks is somewhat different from that shown for the Garibaldi rocks. Within the Caulfeild rocks combination tends to be governed by the Carlsbad, Albite-Carlsbad, and Albite-Ala laws, in the respective ratio of 5:3:2, while the combinations within the Garibaldi volcanics have a ratio of 3:5:2.

However, combination twins within these dioritic rocks are few and are probably formed early in the history of the rock since many of the combinations have partial or complete overgrowths of plagioclase felspar, whose composition is very acid and is comparable to the outer zones of many single crystals of plagioclase (fig. 3).

Metamorphic rocks have been examined for combinations of plagioclase felspars in specimens from the North of Scotland and from the Caulfeild area, but none has been observed.

DISCUSSION

Combinations of plagioclase felspars in twin relationships have rarely been described in the literature dealing with the crystallography and optics of plagioclase. Kohler and Raaz (1947, p. 165), when describing Carlsbad twinning in the plagioclase of some volcanic rocks, noticed that "in addition to common occurrence of Carlsbad twins in individuals, there are also contact twins whose halves are united by the composition plane (010)", and showed that the law governing their combination is Albite-Carlsbad. The results shown in tables 1 and 2 for combination twins from the Garibaldi rocks also show that the common law governing combination is Albite-Carlsbad.

That the plagioclase in the Garibaldi rocks is magmatic in origin is unquestionable. Therefore, since these rocks have a high percentage of phenocrysts of plagioclase there must have been a stage in the crystallization of the lavas when large plagioclase crystals were floating about in a fluid medium, and it is thought that under these conditions combinations of crystals is most likely. Combination is also likely to be governed by other factors such as time taken for complete crystallization of the melt, the viscosity of the melt (which may possibly account for the difference in numbers of combination twins seen in granitic rocks and volcanic rocks), and the shape and form of the crystals.

The shape and form of the plagioclase crystals in the Garibaldi volcanics can be shown to be largely tabular in the a/c plane, such that the (010) face has the greatest surface area, and this, coupled with the fact that the rocks commonly exhibit flow structures, would account for crystal combinations having a composition plane of (010). It is likely that the mode of combination of crystals is one partly determined by chance, but from the frequency of twin laws within the volcanic rocks it would seem that Albite-Carlsbad and Carlsbad combinations are favoured above all others.

Within the Caulfeild dioritic rocks the shape and form of the plagioclase crystals is not so marked as in the Garibaldi volcanics. However, while the (010) face appears to be well-developed, the other faces, (001) and (100), are not developed to the same degree, and therefore any combination that occurs is again likely to have a composition plane of (010).

Relatively few combinations are observed in these dioritic rocks, and many of those that have been examined have a complete overgrowth of plagioclase that is comparable in composition to many of the single crystals of plagioclase. Thus, combination of early formed crystals has occurred, and table 3 shows that the Carlsbad and Albite-Carlsbad are again the favored laws. Possibly the paucity of combinations in the dioritic rocks is due to two factors. In this type of rock centers of crystallization occur throughout the melt and the rate of growth is fairly uniform, as shown by the equigranular texture. Also, the melt is likely to have a relatively high viscosity, such that combination and alignment of crystals is likely to be at a minimum, while random orientation and interpenetration of crystals are at a maximum—the reverse state of affairs probably existing within rocks of the Garibaldi type.

As mentioned earlier, no combination twins were observed in metamorphic or metasomatic rocks, which fact may have some petrogenetic significance. Recently, Gorai (1951) suggested a method whereby metamorphic rocks may be distinguished from truly igneous rocks on the basis of the type of twinning in the plagioclase present in those rocks. If, as is believed by the present author, combination twins in plagioclase result only by combination of crystals suspended in a melt, then the presence or absence of such twins, used in conjunction with the method proposed by Gorai, would be useful in separating truly magmatic rocks from those of metasomatic or metamorphic origin.

References

Gorai, M., 1951, Petrological studies on plagioclase twins: Am. Mineralogist, v. 36, p. 884-901.

Kohler, A., and Raaz, F., 1947, Gedanken über die Bildung von Feldspatzwillingen: Wein p. 163-171.

Mathews, W. H., 1948, The geology of the Garibaldi Area, British Columbia: Unpublished Thesis from California Univ.

Turner, F. J., 1947, Determination of plagioclase with the four-axis universal stage: Am. Mineralogist, v. 32, p. 389-410.

Van der Kaaden, G., 1951, Optical studies on natural plagioclase felspars with high and low-temperature optics: Diss. Univ. Utrecht.

Dept. of Geology
University of British Columbia
Vancouver, British Columbia

[American Journal of Science, Vol. 255, November 1957, P. 656-666]

CORRELATION OF ZONES IN PLAGIOCLASE

H. J. GREENWOOD and K. C. McTAGGART

ABSTRACT. The compositions and sequences of zones in plagioclase crystals were measured and an attempt made to correlate zone sequences from one crystal to another in the same rock. Correlation was found to be high in hornfels and gneiss. Low correlation of plagioclase crystals in lavas and some granitic intrusions is probably the result of mixing of crystals formed in different environments. Rocks in which adjacent plagioclase crystals are consistently of low correlation are probably magmatic rather than metamorphic. Quartz diorites near Vancouver, B. C. show notable correlation over a distance of at least two miles, indicating something of the minimum dimensions of the system within which similar feldspar-forming reactions take place in such rocks. The plagioclase of hornfels and gneiss may show normal or reverse zoning.

INTRODUCTION

The purpose of the present study is to compare the zoning of plagioclase in different types of rock and to test the possibility of correlating the sequence of zones from one crystal to another.

Phemister's (1945) detailed account of the batholithic and metamorphic rocks at Caulfeild, some 7 miles northwest of Vancouver, B. C., includes some discussion (p. 65) of the nature and significance of zoning in plagioclase, and his brief consideration of the variation of zoning from place to place stimulated the present research. Preliminary studies were started by Chamberlain (1955) and these were revised and greatly expanded with the results presented below. Early in the work, W. H. Mathews pointed out that the feldspars of certain of the volcanic rocks of Garibaldi Park, B. C. showed different sequences of zoning in a single thin-section. Some of these were restudied and the results are included here.

METHOD OF STUDY

Plagioclase was examined using a four-axis universal stage and the Rittmann zone method (Emmons, 1943, p. 115). Thin sections were first examined with an ordinary petrographic microscope. Crystals of plagioclase that showed a wide range of zones (the thin-section apparently cutting through the middle of a crystal), that were oriented more or less perpendicular to (010), and that had some indication of (001) cleavage or pericline twinning, were sketched and their locations in the thin section noted. The selected grains were then oriented on a universal stage so that crystallographic 'a' was parallel to the axis of the microscope. The angle between the direction of the fast ray, X′, and the trace of (010) was measured for successive zones from the margins of the crystals to the cores. These extinction angles were plotted as ordinates against widths of zone as abscissae, with the margins of the crystals to the left. The compositions of the zones may be determined directly from the extinction angles, using such curves as Emmons' (1943, p. 121) or Van der Kaaden's (1951, p. 52).

Certain difficulties are met in carrying out these apparently simple operations. A thin section may contain few or no crystals of suitable orientation, and several sections may have to be examined. It is impossible to measure extinction angles of narrow zones more closely than 2 or 3 degrees. Checks on the accuracy of some of the measurements were made by measuring sequences

of zone-angles from opposite ends of the same crystal (cf. 7, 9, 10, 28)[1] where such pairs of sequences are marked by asterisks) or by measuring compositions of individual zones using the methods of Turner (1947). Narrow zones cut at oblique angles so that zones overlap in the line of sight are unusable. Very complex and narrow zoning is impossible to measure and can only be represented schematically. In certain of the granitic rocks, plagioclase is partly replaced by late K-feldspar, resulting in removal of some of the outer zones.

[1] The numbers refer to the curves of figures 3, 4, 5, and 6.

DEGREE OF CORRELATION

For a given thin section or series of thin sections, the original curves were replotted; the zone widths were widened or narrowed, and the conspicuous surfaces of corrosion (indicated by vertical sinuous lines) were taken into account, so that the highest correlation is obtained. In (28), for example, the parts removed by corrosion are indicated by breaks in the zone curve.

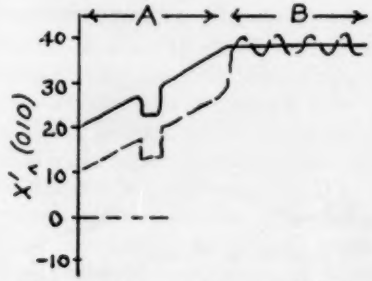

Fig. 1. Form vs. value correlation.

Estimation of the degree of correlation is difficult. Two factors to be considered are form or shape, and value. Two curves (fig. 1) may show high form correlation but low value correlation (A), or high value correlation but low form correlation (B). Various graphical methods of evaluating degree of correlation were tried, but none proved satisfactory, and the final evaluation of degree of correlation was made by eye, admittedly a highly subjective method. The subjective element in measuring the extinction angles, preparing the curves for estimation, and estimating the degree of correlation is illustrated by the fact that Chamberlain, who carried out preliminary work on certain of the Caulfeild rocks, concluded that there was no correlation at all, whereas it is here maintained that there is significant correlation.

Where there are more than about 5 curves on a single chart, the result is so confusing that for certain examples average curves representing several similar curves are derived by averaging ordinate values at regular intervals. By careful and unscrupulous adjustment, of course, the original curves may be arranged so that the average curves will show almost any configuration.

THE ROCKS STUDIED

Although zone curves were plotted for the feldspars of a great many specimens, only about one-quarter of the curves seem to be sufficiently in-

teresting to present here. Most of the work was done on single specimens and single thin-sections but many specimens from the accessible batholithic and related rocks near Vancouver were studied. Brief descriptions of the rocks for which curves are shown are given below.

Hornfels.—In only three of 25 specimens of hornfels examined is the plagioclase clearly zoned. One is from Kwoiek Creek, west of Lytton, B. C., at the eastern margin of the Coast Range batholithic complex. It (1) is a hornblende-plagioclase hornfels with garnet porphyroblasts. The other two (2 and 3) are from Harrison Lake, B. C. where cordierite-anthophyllite hornfels is produced in Jurassic sedimentary rocks at a contact with a Tertiary (?) quartz-diorite stock.

Gneiss.—The plagioclase of most of what are interpreted as metamorphic gneisses available to the writers is unzoned. Two specimens with zoned feldspar are from the Terrace area, northern B. C., about 2 miles from the eastern

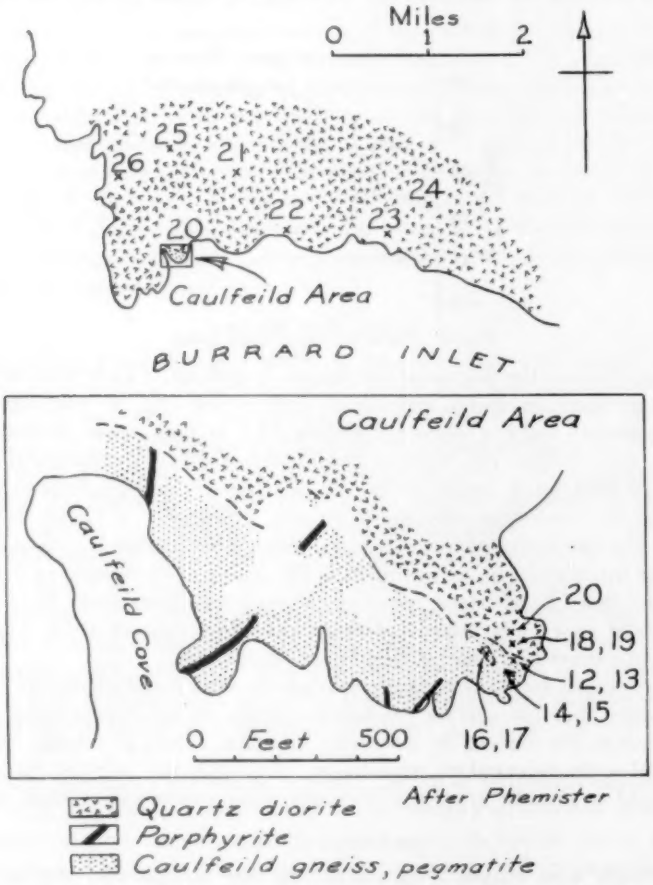

Fig. 2. Geology around Caulfeild, near Vancouver, B. C.

margin of the Coast Range intrusions. One (4) is from a foliated layer of granitic composition and the other (5) from a fine-grained amphibolitic layer, both derived from volcanic rocks. One specimen (6), a paragneiss, is from the Glenlyon Range, in Yukon Territory. Three specimens of gneiss from Caulfeild, (12, 13 and 17) near Vancouver, are described below.

Granitic Rocks.—Zone curves are shown for a group of probably magmatic granitic rocks, from various localities, and also for specimens from Caulfeild.

A specimen (7) from Ben Nevis, a cauldron subsidence type of intrusion, is from the inner part of the "Inner Granite". Specimen (8) from the Shap granite, exact locality unknown, shows large feldspar phenocrysts and rounded quartz grains. The plagioclase studied is in the granular groundmass. The Pilchuck granite (9) is from a stock in Washington, U. S. A., that intrudes and alters to hornfels Lower Cretaceous shale. Specimen (10) is of a porphyritic dyke exposed in the Fraser Canyon, north of Hope, B. C. A specimen (11) of quartz diorite from Harrison Lake, B. C. is from the Tertiary (?) stock already mentioned in connection with the hornfels from that locality.

Rocks near Caulfeild, B. C.—Quartz diorites of the Coast Range batholithic complex are exposed along the north side of Burrard Inlet at Vancouver, B.C. At Caulfeild (fig. 2) they are in contact with highly metamorphosed pre-batholithic rocks. These, referred to by Phemister as the Caulfeild gneiss, are probably part of a large inclusion. Porphyrite dykes intrude the gneiss but appear to be older than the batholithic rocks.

The Caulfeild gneiss is a well-banded, fine-grained, grey to black rock composed essentially of hornblende and calcic plagioclase. The texture is mosaic with a marked preferred orientation of hornblende parallel to the banding. Gneisses and the contact strike westerly and dip nearly vertically.

Quartz diorite in the vicinity of Caulfeild is medium-grained and granitic in texture and consists mainly of andesine with subordinate K-feldspar, quartz, biotite, and minor hornblende. Dark grey rounded inclusions, mostly less than 1 foot in diameter, are scattered through the quartz diorite. Large, elongate inclusions of porphyrite show a general parallelism to the dykes in the gneisses at Caulfeild and elsewhere, and the foliation of the not abundant inclusions of gneiss is parallel to the regional westerly strike of the pre-batholithic rocks.

At Caulfeild, the gneiss is intruded by pegmatite and aplite, and by dykes up to a few feet wide of quartz diorite, some of which show dilation offset. Other intrusions of quartz diorite (one is referred to below as the 'inclusion dyke'), irregular in plan, many feet across, are crowded with inclusions of gneiss. Some of these inclusions can be fitted back into their original positions in the intrusion walls, thus providing clear evidence of mobility of the quartz diorite matrix.

Plagioclase zoning in the gneiss (two specimens, several feet apart (12 and 13), in a dilation dyke (two specimens, 2 feet apart, (14 and 15), in quartz diorite and gneiss components of the 'inclusion dyke' (16 and 17), in a rounded inclusion in the quartz diorite some 25 feet from the contact (18), and in the botholithic quartz diorite (19 to 26) were studied. The localities are shown in figure 2. The study could be extended over a much wider area

but the results so far obtained seem to be of sufficient interest to be made known here.

Lavas.—The plagioclase phenocrysts of several lavas were studied and the zone curves of those described below are believed to be representative of the group.

Three specimens of Pleistocene andesites (28, 29 and 30) from Garibaldi Park, north of Vancouver, consist of strongly zoned plagioclase phenocrysts set in a matrix of plagioclase microlites, minor biotite, and glass.

A specimen of Tertiary andesite (31) from Cotton Ranch, in the Chilcotin area in west central B. C., is porphyritic with trachytic groundmass and consists largely of plagioclase, minor oxyhornblende, and cryptocrystalline material.

The fifth specimen (32) is of the Markle basalt from the Markle quarry, East Lothian, Scotland. It is a reddish lava with abundant plagioclase phenocrysts, up to 5 mm across, set in an aphanitic groundmass.

DISCUSSION OF ZONE CURVES

Within indivdual crystals correlation is relatively high (see 7, 9, 10 and 28), but there are small but notable differences. Barber's (1936) examples of single zoned crystals from andesite show almost perfect correlation. Yeats (1957, p. 41) states that in certain magmatic rocks "individual zones and zonal sequences in the same or adjacent crystals sometimes cannot be correlated".

The zone curves for hornfelses and gneisses show high correlation in both form and value. Unzoned crystals, of course, show high form correlation and possibly high value correlation but very few of these have been measured. One example of gneiss (6) shows high internal correlation but lower external correlation. It is noteworthy that surfaces of corrosion or unconformities, as shown by truncated inner zones, are not restricted to magmatic rocks, but are found also in gneiss (4 and 5). The curves presented here for metamorphic rocks show mostly normal zoning but also reverse zoning and suggest that in zoned crystals the relative frequencies of the two types are not very different from those in igneous rocks. There is no evidence here that formation of the feldspars of hornfels and gneiss took place during rising rather than falling temperatures. The zoning of the small inclusion (17) in the 'inclusion dyke' is more complex than the zoning of the main mass of Caulfeild gneiss (12 and 13) but all these are less complex than the zoning of the surrounding or adjacent quartz diorite. Similarly, there is little correspondence between the simple zoning of the Harrison hornfels (2 and 3) and the complex zoning of the intrusion (11). However, zoning of the rounded inclusion (18) is somewhat similar to that of the feldspar of the enclosing quartz diorite.

The grained igneous rocks (Ben Nevis, Shap, Pilchuck and Hell's Gate) show moderate to high correlation within individual thin-sections (7, 8, 9, and 10). The Shap granite shows moderate form correlation but low value correlation and the Pilchuck granite high form and value correlation.

Quartz diorites near Caulfeild show some variety in degree of correlation. The 8-inch wide dilation dyke, within the Caulfeild gneiss, shows moderate

correlation within each of two specimens (14 and 15) some 2 feet apart and one conspicuous zone is common to both.

A specimen of quartz diorite from the 'inclusion dyke' (16) shows mod-

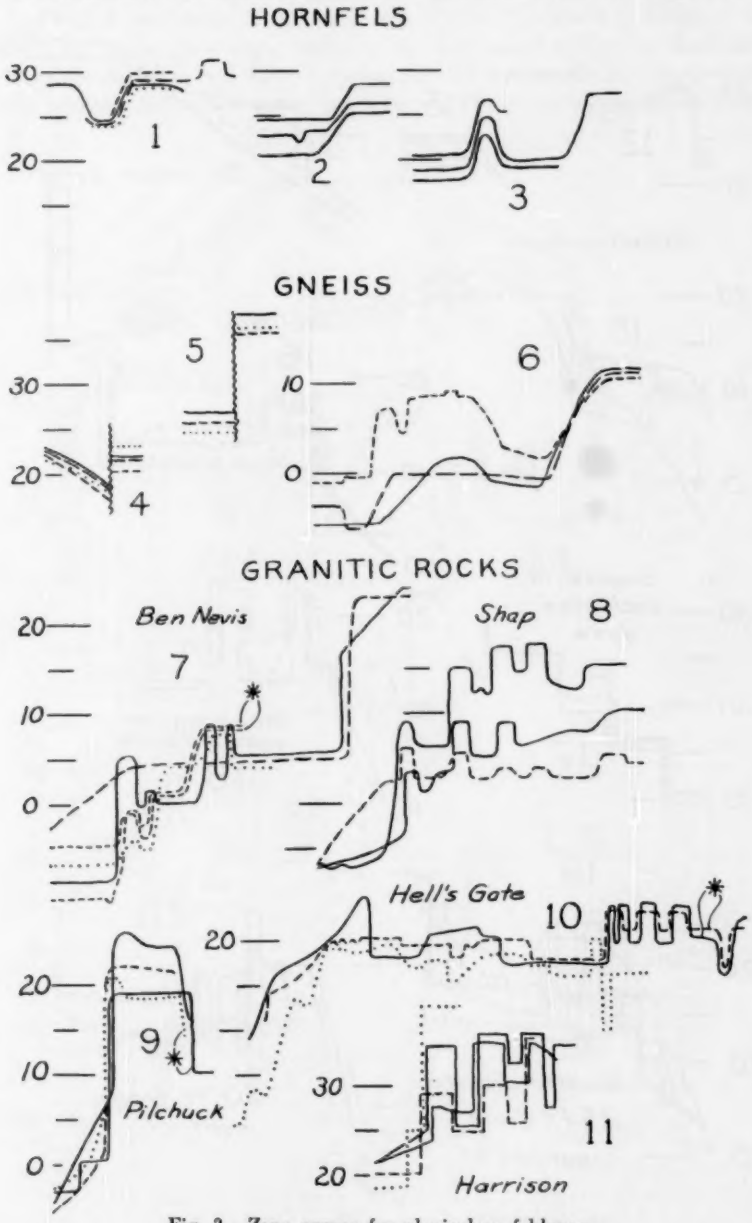

Fig. 3. Zone curves for plagioclase feldspars.

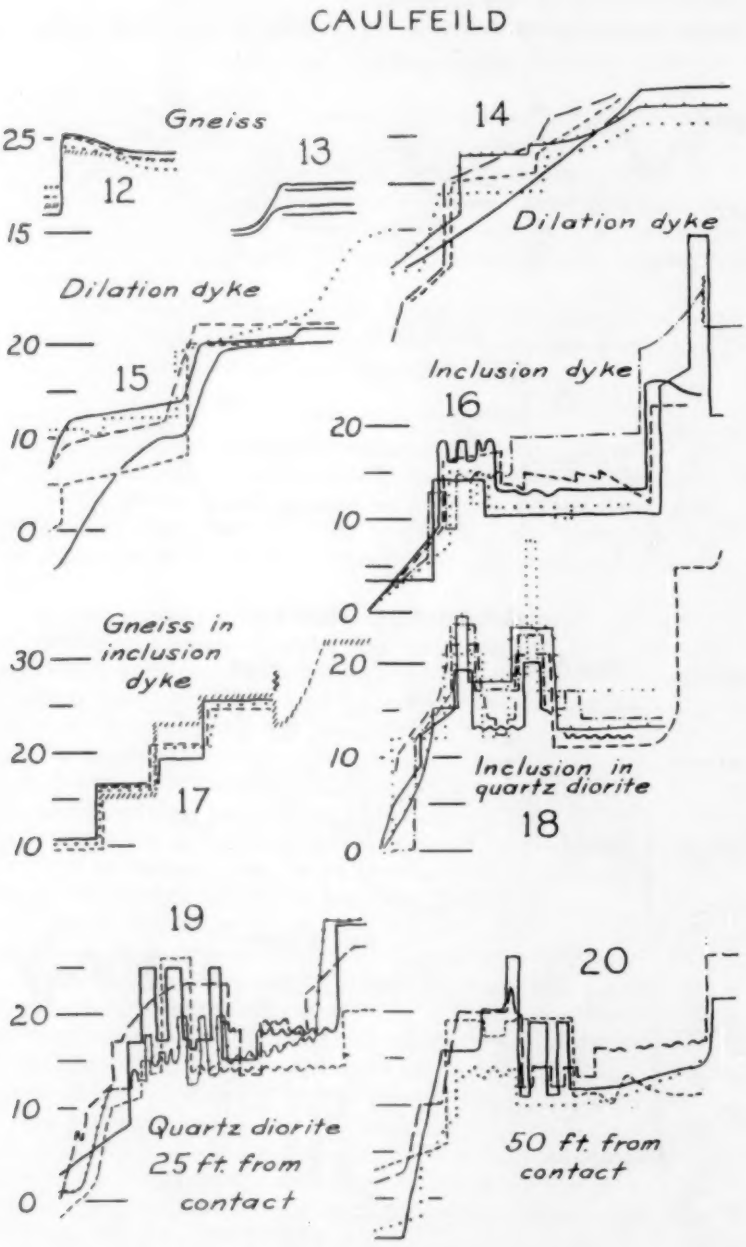

Fig. 4. Zone curves for plagioclase feldspars.

erate correlation between four crystals (after considerable adjustment of zone widths) but one crystal differs markedly and is possibly a modified xenocryst. The general pattern is similar to that of the quartz diorite of the batholith.

Individual specimens of quartz diorite (19 to 26) north and east of the Caulfeild inclusion show some variation in their zoned feldspars. Most show low to moderate form and value correlation. One specimen (24), particularly reliable because individual zones are recognizable by their inclusions, shows

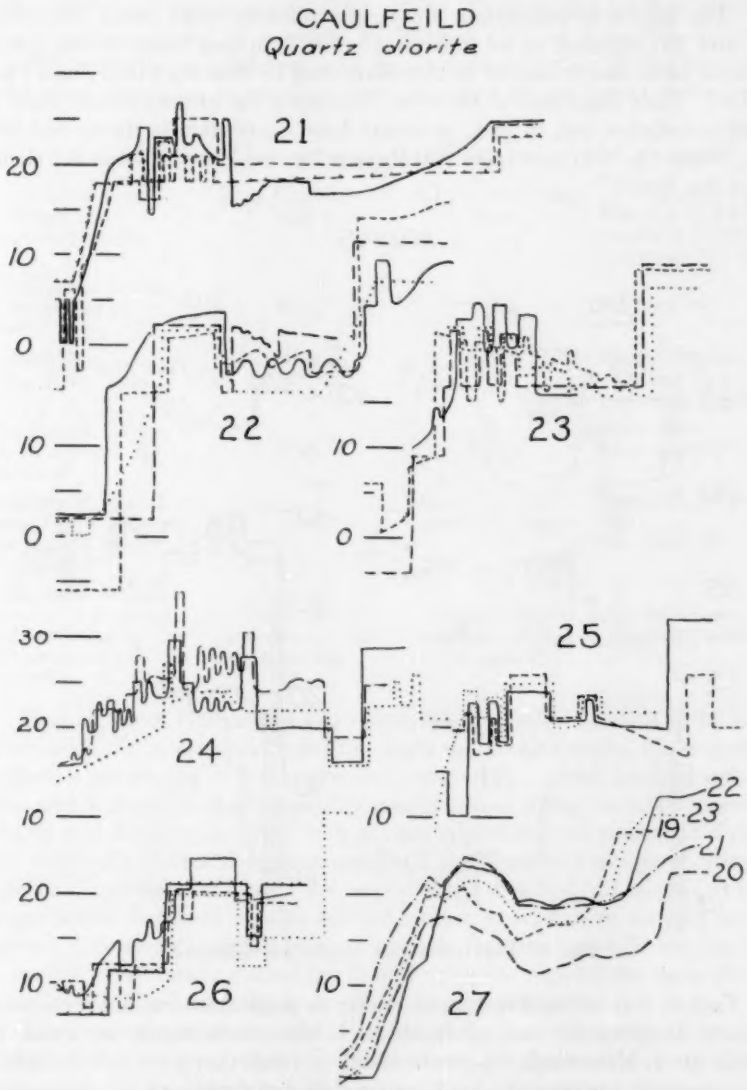

Fig. 5. Zone curves for plagioclase feldspars.

moderate form and value correlation in general, but many differences in detail. One example (25) shows in large part high form correlation and moderate to high value correlation.

The zone curves of specimens 19 to 23 show a general similarity that is brought out by comparing average curves (27) for each of the specimens. This general similarity is believed to indicate that similar, but not identical conditions of crystallization, existed over the area encompassing the points at which the specimens were collected, about two miles by one mile.

The degree of correlation among the volcanic rocks tested (28, 29, 30, 31, and 32) appears to be somewhat lower than that found in the grained igneous rocks and is similar to that illustrated by Homma (1931) and Paliuc (1931). Their diagrams, of the type illustrating the present paper, show low value correlation but, in part, moderate form correlation in dacite and andesite. Paliuc (p. 438) concludes that there is "grosse Variabilität in der Reihenfolge der Zonen".

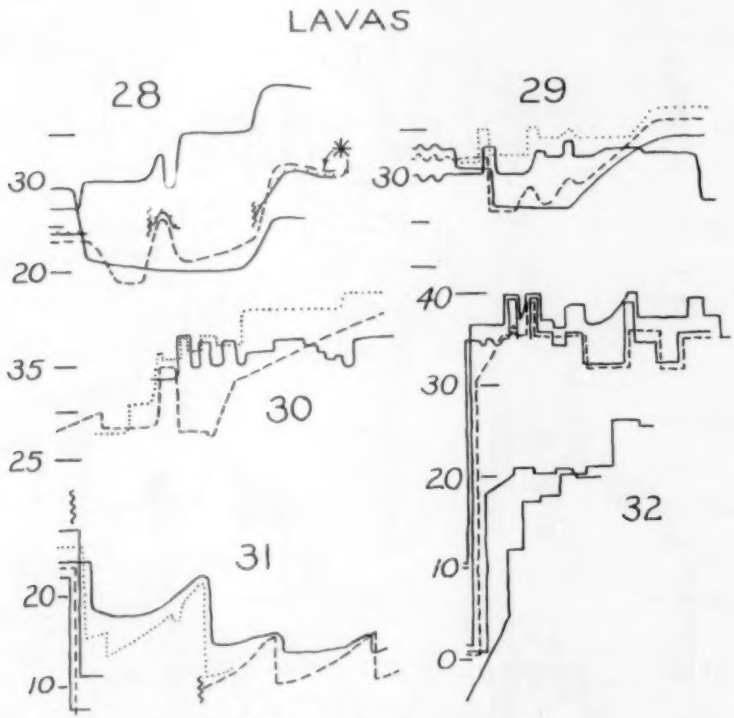

Fig. 6. Zone curves for plagioclase feldspars.

Factors that are said to control zoning in plagioclase include variation in pressure, temperature and composition in the environment in which the crystals grew. Metamorphic or metasomatic crystals that grow side by side in a homogeneous metamorphic rock, or crystals that develop in a homogeneous

magma in which there was no relative movement of crystals, would seem to be subject to similar variations in environment and should show high correlation in their zone curves. Crystals that grow in persisting different chemical environments, but subject to similar variation in temperature and/or pressure, would be expected to show high form correlation but low value correlation. Such an environment might exist in a non-homogeneous metamorphic rock or in a magma where crystals are growing around nuclei of different compositions and where compositional differences persist in the melt within the domain or region of crystallization (Hills 1936). Crystals that grow in entirely different environments, for example in different parts of a magma chamber or in different magma chambers, and finally come together during intrusion or extrusion, might be expected to show little correlation except in the outer zones.

TABLE 1

Environment	Form Correlation	Value Correlation	Examples
Metamorphic homogeneous rocks	High	High	Hornfels (1, 2 & 3) Gneiss (4, 5, 12, 13) Inclusions (17, 18)
Static Magma, i.e. no relative motion of crystals	High	High	Pilchuck (9)
Metamorphic heterogeneous rocks	High	Lower	Caulfeild gneiss, (12) and (13) considered together
Static Magma, having seeds of a range of composition	High	Lower	Shap (8) ?, Chilcotin (31) ?
Convecting or stirred magma, crystals move relatively and finally come together	Low	Inner zones: Low; Outer zones: High	Lavas (28, 29, 30, 32) Ben Nevis (7)
Magma, some relative movement of crystals; overall variation in environment affects all crystals	Low in detail, moderate or high in general	Low in detail, moderate or high in general	Caulfeild quartz diorite (19 to 23, *see* (27)

Most of these generalizations, summarized in table 1, seem to be compatible with the zone curves resulting from the present study, the degree of correlation decreasing in the sequence: metamorphic rocks, grained igneous rocks, and volcanic rocks, reasonably considered as a sequence of increasing mobility and distance of travel, with greater opportunity of mixing of crystals from originally different environments. Of the Caulfeild quartz diorites, it might be suggested that during the emplacement of a body of magma at least 2 miles across there was enough relative motion of crystals to account for the observed differences in detail between crystals that are now adjacent but that the overall environment varied fairly uniformly throughout the mass during crystallization, producing the gross similarity of zone curves.

These considerations suggest a means of distinguishing magmatic rocks in which there has been relative motion of crystals from other magmatic or metamorphic rocks. Rocks in which adjacent plagioclase crystals consistently

show low correlation are probably magmatic. Rocks in which adjacent plagioclase crystals show high correlation may be either magmatic or metamorphic.

CONCLUSIONS

1. Correlation of plagioclase zones is highest in metamorphic rocks. The feldspars of some granitic intrusions and many lavas show low correlation, probably the result of mixing of feldspar crystals formed in different environments.

2. Rocks in which adjacent plagioclase crystals are consistently of low correlation are probably magmatic rather than metamorphic.

3. Quartz diorites near Caulfeild show similar feldspar zone curves over a distance of at least 2 miles, suggesting something of the minimum dimensions of the system within which similar feldspar-forming reactions take place in such rocks.

4. The plagioclase of hornfels and gneiss may show reverse zoning or normal zoning. Some metamorphic plagioclase apparently grew while rock temperatures were falling.

REFERENCES

Barber, C. T., 1936, The Tertiary rocks of the Pakokku District and the Salingyi Township of the Lower Chinwin District, Burma, with special reference to the determination of the feldspars by the Federoff method: Geol. Survey of India Mem., v. 68, pt. 2, p. 121-292.

Chamberlain, Joseph, 1955, Unpublished Bachelor's Thesis, Univ. of British Columbia.

Emmons, R. C., 1943, The universal stage: Geol. Soc. America Mem. 8.

Hills, E. S., 1936, Reverse and oscillatory zoning in plagioclase feldspars: Geol. Mag., v. 73, p. 49-56.

Homma, F., 1932, Über das Ergebnis von Messungen and zonaren Plagioklasen aus Andesiten mit Hilfe Universaldrehtisches: Schweizerische Mineralogische und Petrographische Mitteilungen, Band 12, p. 345-352.

Paliuc, G., 1932, Untersuchen der Plagioklase einiger Tertiärer Ergussgesteine Siebenburgens (Roumänien) der Universaldrehtischmethode: Schweizerische Mineralogische und Petrographische Mitteilungen, Band 12, p. 423-444.

Phemister, T. C., 1945, The Coast Range batholith near Vancouver, British Columbia: Geol. Soc. London Quart. Jour., v. 101, p. 37-88.

Turner, F. J., 1947, Determination of plagioclase with the four-axis universal stage: Am. Mineralogist, v. 32, p. 389-410.

Van der Kaaden, G., 1951, Optical studies on natural plagioclase feldspars with high- and low-temperature-optics: Diss. Univ. Utrecht.

Yeats, R. S., 1957, Euhedral oscillatory zoning in igneous plagioclase: Abstracts of papers Cordilleran Sect., Geol. Soc. America, Los Angeles, Cal., April 19-20, p. 41.

Department of Geology
University of British Columbia
Vancouver 8, Canada

COMMUNICATION

CORRELATION OF CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF DOLOMITE

A reader has recently called my attention to a major weakness in the regression equations contained in my article, "Correlation of chemical composition and physical properties of dolomite" (this JOURNAL, v. 254, p. 51). I hope that this note will serve to prevent any possible misconstruction.

The point is that the regression equations were based on five sets of data only. As the carbonate system discussed contains three components and thus defines a plane in the compositional space, this means that only two degrees of freedom are available for testing the equations, an inadequate number, especially in view of the small numerical differences in the data.

Perhaps this is an opportune moment to enter a plea for more data on this subject, whose importance may be measured by the number of recent papers on carbonates. Without the detailed numerical data, no amount of speculation or extrapolation will lead to valid conclusions.

E-AN ZEN

DEPARTMENT OF MINERALOGY
HARVARD UNIVERSITY
CAMBRIDGE 38, MASS.

REVIEWS

La Physique de l'Atmosphère. Vol. I. Emission phenomena in the atmosphere; by ETIENNE VASSY. P. vi, 338. Paris, 1956 (Gauthier-Villars, 3.500 fr.).—The author sets himself and accomplishes the task of selecting from the increasingly complex literature on atmospheric phenomena those topics which are of greatest interest for the student today and form the basis for current research. He deals with the structure of the atmosphere, the Northern Lights, the light of the night sky, emission phenomena in twilight, from meteors and lightning. Explanations are simple and graphic, and the development of the subject is such that even a reader whose interest is centered in other fields will find the book absorbing and rewarding. HENRY MARGENAU

The Granite Controversy: Geological Addresses Illustrating the Evolution of a Disputant; by H. H. READ P. xix, 430; 23 figs. New York, 1957 (Interscience Publishers, Inc., $6.75).—The job of the reviewer is very prosaic in dealing with Professor Read's collection of essays, because the author himself, in an informative yet concise and graceful introduction, has summarized the development of his point of view and evaluated its significance. Since this book brings together within hard covers Read's eight major addresses on granite, metamorphism, and plutonic geology, each one of which in its turn influenced and is familiar to all geologists interested in these subjects, it only remains to point out how pleasant and useful it is to have them attractively printed and bound in book form with the addition of thirty pages of bibliography and index as well as the introduction. I feel sure these papers will long be regarded as classics because of the freshness with which they present profound and imaginative speculative thought, tempered by real insight into the relevant geologic relations, and this freshness will remain long after the thought itself becomes commonplace through assimilation into the workaday conceptual substratum of geology. The papers included in the volume are:

Metamorphism and igneous action (1940)
Meditations on granite: part one (1943)
Meditations on granite: part two (1944)
Granites and granites (1948)
A commentary on place in plutonism (1948)
A contemplation of time in plutonism (1949)
Metamorphism and granitization (1951)
Granite series in mobile belts (1955)

MATT WALTON

Publications Recently Received

Organic Chemistry; by H. Harry Szmant. New York, 1957 (Prentice-Hall Inc., $7.95).
College Physics; by Robert T. Beyer and A. O. Williams, Jr. New York, 1957 (Prentice-Hall Inc., $7.50).
Journal of a Scientician; by Piero Modigliani. New York, 1957 (Philosophical Library, $3.75).
Light Scattering by Small Particles; by H. C. van de Hulst. New York, 1957 (John Wiley & Sons, $12.00).
Modern Applied Photography; by G. A. Jones. New York, 1957 (Philosophical Library, $4.75).

Mécanique Ondulatorie du Photon et Théorie Quantique des Champs; by Louis de Broglie. Paris, 1957 (Gauthier-Villars, 2.900 fr.).

Geology of India and Burma; by M. S. Krishnan. Madras, 1956 (Higginbothams, Ltd., Rs. 22/8).

Public and Industrial Ground-Water Supplies of the Roanoke-Salem District, Virginia; by Bruce F. Latta. Charlottesville, 1956 (Virginia Division of Geology Bull. 69).

Report of the Geological Survey Branch for the year 1953. Perth, 1956 (Dept. of Mines of Western Australia).

Subsurface Correlations Based on Selected Well Logs from the Eastern Shore Peninsula, Virginia; by Allen Sinnott and G. Chase Tibbitts, Jr. Charlottesville, 1957 (Virginia Division of Mineral Resources, Circular No. 6).

Transactions and Proceedings of the Geological Society of South Africa, vol. 59. Johannesburg, 1956.

Elasticity, Fracture and Flow; by J. C. Jaeger. New York and London, 1957 (John Wiley & Sons, Inc. and Methuen & Co., $2.50).

Investigacion sobre lateritas fosiles en las regiones sureste de Oaxaca y sur de Chiapas; by Benjamin N. Webber and Jesus Ojeda Rivera. Mexico, 1957 (Inst. Nacional para la Investigacion de Recursos Minerales, Bol. 37).

The Aleut Dentition; by Coenraad F. A. Moorrees. Cambridge, 1957 (Harvard University Press, $4.50).

William Harvey; by Louis Chauvois. New York, 1957 (Philosophical Library, $7.50).

An Introduction to Qualitative Analysis; by T. R. Hogness and Warren C. Johnson. New York, 1957 (Henry Holt and Company, $5.75).

Genetics; by Edgar Altenburg. New York, 1957 (Henry Holt and Company, $6.50).

Matter and Energy; by Arthur Talbot Bawden. New York, 1957 (Henry Holt and Company, $3.95).

Principles of Modern Biology, 3d edition; by Douglas Marsland. New York, 1957 (Henry Holt and Company, $6.50).

Principles of Stratigraphy; by Carl O. Dunbar and John Rodgers. New York, 1957 (John Wiley and Sons, Inc., $10.00).

Principles of Immunology; by John E. Cushing and Dan H. Campbell. New York, 1957 (McGraw-Hill Book Co., $6.50).

The American Teenager; by H. H. Remmers and D. H. Radler. Indianapolis, 1957 (Bobbs-Merrill Company, $3.75).

A Survey of the Iron Ore Industry in Canada During 1956; by T. H. Janes. Ottawa, 1957 (Department of Mines and Tech. Surveys).

Geologic Field Methods; by Julian W. Low. New York, 1957 (Harper & Brothers, $6.00).

Lecture Notes on the Use of the Microscope; by R. Barer. Springfield, Ill., 1957 (Charles C. Thomas, $1.50).

General Chemistry; by A. W. Laubengayer, revised edition. New York, 1957 (Rinehart & Co., $6.50).

Illinois Geol. Survey, Rept. of Investigations: 200, Chemical Analyses of Illinois Limestones and Dolomites; compiled by J. E. Lamar. 201, Types of Late Cenoizic Gastropods in the Frank Collins Baker Collection; by A. Byron Leonard. Urbana, 1957.

Glossary of Geology and Related Sciences. Washington, D. C., 1957 (American Geological Institute, $6.00).

Bibliography of Fossil Algae: 1942-1955; J. Harlan Johnson. Golden, Colorado, 1957 (Quarterly Colorado School of Mines, $1.00).

Introduction to Electrical Applied Physics; by N. F. Astbury. New York, 1957 (Philosophical Library, $10.00).

New Zealand Geol. Survey Bulletins: 28, Studies in New Zealand Foraminifera; by Paul Vella. 57, Petrology of the Lower Mesozoic Rocks of the Wellington District; J. J. Reed. Wellington, 1957.

Les Facteurs de la Croissance Cellulaire; edited by J. André Thomas. Paris, 1956 (Masson et Cie, 4.000 fr).

Los Yacimientos de Estano en el Estado de Durango; by Ward C. Smith, Reynaldo Guiza, Jr., and Kenneth Segerstrom. Mexico, 1957 (translated into Spanish by Salvador Ullea for the Inst. Nacional para la Investigacion de Recursos Minerales, Bol. 36).

Science Reports of Tohoku University, vol. V, no. 3. Sendai, Japan, 1957.

The Political Geography of the Yucatan Maya; by Ralph L. Roys. Washington, D. C., 1957 (Carnegie Institution of Washington, $1.60 paper).

Elemetary Soil and Water Engineering; by Glenn O. Schwab, Richard K. Frevert, Kenneth K. Barnes and Talcott W. Edminister. New York, 1957 (John Wiley and Sons, $6.25).

Ground-Water Levels in Observation Wells in Kansas, 1956; by V. C. Eischel and Betty J. Mason. Lawrence, 1957 (State Geol. Survey of Kansas, Bull. 125).

Geology and Ground-Water Resources of Central-East Georgia; by H. E. LeGrand, A. S. Furcon, R. F. Carter and A. C. Lendo. Atlanta, 1956 (Geological Survey of Georgia, Bull. 64).

Anthropological Papers; edited by Robert Anderson. Salt Lake City, 1956 (University of Utah).

Petroleum Industry in Illinois in 1955. Urbana, 1957 (Illinois Geol. Survey, Bull. 81).

Niels Hendrik Abel, Mathematician Extraordinary; by Oystein Ore. Minneapolis, 1957 (University of Minnesota Press, $5.75).

The Living Rocks. New York, 1957 (Philosophical Library, $6.00).

Acoustics; by Joseph L. Hunter. New York, 1957 (Prentice-Hall, Inc., $8.50).

Canada Dept. of Mines, Mineral Resources Information Circulars: 23, A Survey of the Petroleum Industry in Canada During 1956; by R. B. Toombs and R. A. Simpson. 24, A Survey of the Natural Gas Industry in Canada During 1956; by R. B. Toombs and R. A. Simpson. Ottawa, 1957.

Physics for Science and Engineering; by Robert L. Weber, Marsh W. White and Kenneth V. Manning. New York, 1957 (McGraw-Hill Book Co., $8.00).

Mysteries of Science; by John Rowland. New York, 1957 (Philosophical Library, $6.00).

Organic Reactions, Vol. IX; Roger Adams, editor. New York, 1957 (John Wiley & Sons, $12.00).

Chemistry; by Michell J. Sienko and Robert A. Plane. New York, 1957 (McGraw-Hill Book Co., $6.75).

Fundamentals of Mechanical Design; by Richard M. Phelan. New York, 1957 (McGraw-Hill Book Co., $8.75).

Détermination Pratique des Fossiles; by André Chavan and André Cailleux. Paris, 1957 (Masson et Cie, 5,800 fr.).

Colorado Bureau of Mines Annual Report, 1956. Denver, 1957.

Mathematics for Science and Engineering; by Philip L. Alger. New York, 1957 (McGraw-Hill Book Co., $5.50).

A Book of Contemplation; by Dagobert D. Runes. New York, 1957 (Philosophical Library $3.00).

Boundary Control and Legal Principles; by Curtis M. Brown. New York, 1957 (John Wiley & Sons, Inc., $7.50).

Miocene Fossils of Maryland; by Harold E. Vokes. Baltimore, 1957 (Dept. of Geology Bull 20).

Vertebrates of the United States; by W. Frank Blair, Albert P. Blair, Pierce Brodkorb, Fred R. Cagle and George A. Moore. New York, 1957 (McGraw-Hill Book Co., $12.00).

Divisão de Fomento da Producao Mineral Bulls. 96, 98, 99, 149, 151. Rio de Janeiro, 1954-55.

Prehistoric Man; by Andre Leroi-Gourhan. New York, 1957 (Philosophical Library, $4.75).

Bull. No. 13, Geol. Survey of Great Britain. London, 1957 (Her Majesty's Stationery Office, 6 shillings).

Divisão de Geologia e Mineralogia, Bols. 151-159. Rio de Janeiro, 1956.

Geology of a Part of the Manly Peal Quadrangle, Southern Panamint Range, California; by Bradford K. Johnson. Berkeley, 1957 (University of California Press).

Systematic Organic Chemistry; by Hugh C. Muldoon and Martin I. Blake. New York, 1957 (McGraw-Hill Book Co., $7.75).

An Introduction to Reactor Physics; by D. J. Littler and J. F. Raffle. New York, London, 1957 (McGraw-Hill Book Co., and Pergamon Press, Ltd.).

Radiation Sheilding; by B. T. Price, C. C. Horton and K. T. Spinney. New York, 1957 (Pergamon Press, $10.00).

Angular Momentum in Quantum Mechanics; by A. R. Edmonds. Princeton, 1957 (Princeton University Press, $3.75).

Medical Radiation Biology; by Friedrich Ellinger. Springfield, Ill., 1957 (Charles C. Thomas, $20.00).

Fundamentals of Optics, third edition; by Francis A. Jenkins and Harvey E. White. New York, 1957 (McGraw-Hill Book Co., $8.50).

Basic Mathematics for Radio and Electronics; by F. M. Colebrook and J. W. Head. New York, 1957 (Philosophical Library, $6.00).

Glass Reinforced Plastics; edited by Phillip Morgan. New York, 1957 (Philosophical Library, $15.00).

VOL. 255 No. 9, 1957

American Journal of Science

NOVEMBER 1957

CONTENTS

Possible Permian Climatic Zonation and its Implications
Francis G. Stehli 607

Temperature Estimation of Pyroclastic Deposits by Natural Remanent Magnetism ..... *Shigeo Aramaki and Syun-iti Akimoto* 619

Experimental Determination of Kyanite-Sillimanite Equilibrium Relations at High Temperatures and Pressures
S. P. Clark, E. C. Robertson and Francis Birch 628

Early Miocene Entelodonts, Texas Coastal Plain .... *John Andrew Wilson* 641

Combination Twinning in Plagioclase Felspars ..... *J. V. Ross* 650

Correlation of Zones in Plagioclase
H. J. Greenwood and K. C. McTaggart 656

COMMUNICATION

Correlation of Chemical Composition and Physical Properties of Dolomite .... *E-anZen* 667

REVIEWS

La Physique de l'Atmosphère; by Etienne Vassy ..... *Henry Margenau* 668

The Granite Controversy; by H. H. Read ..... *Matt Walton* 668

PUBLICATIONS RECENTLY RECEIVED 668